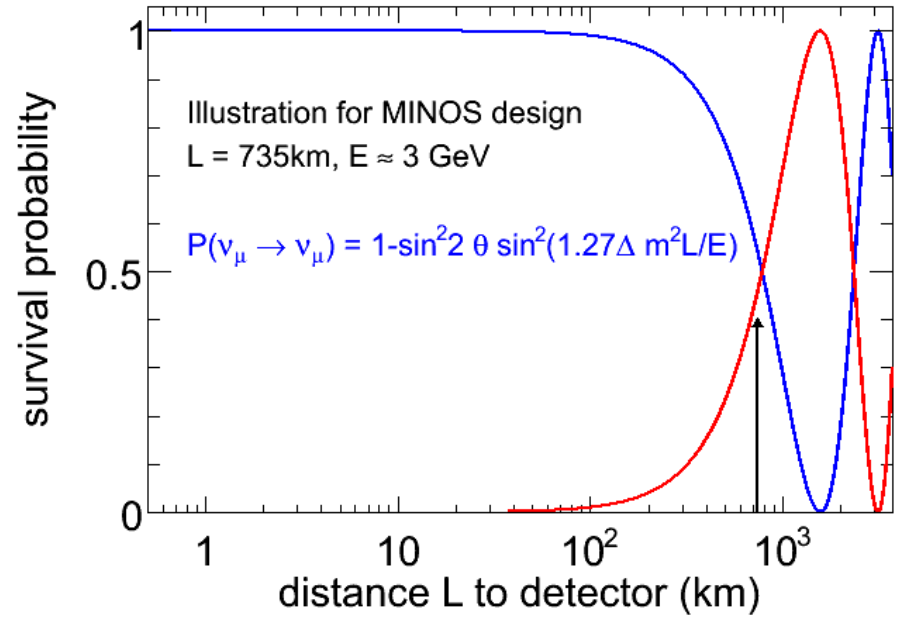
Recent neutrino oscillation results from MiniBooNE and MINOS

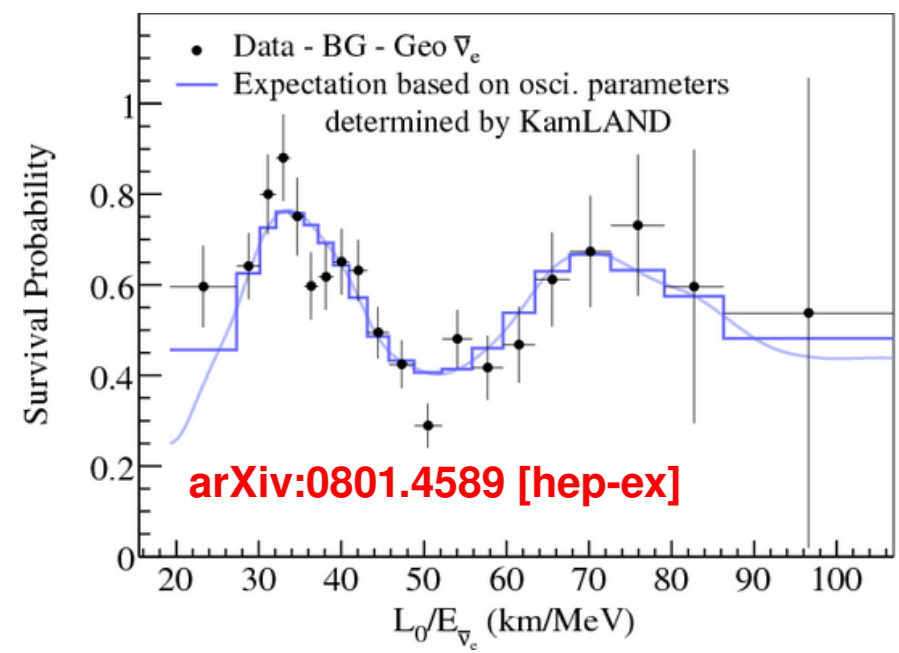
Rustem Ospanov

University of Texas at Austin

Neutrino oscillations: disappearance

- Experiments in Homestake, Kamioka and Sudbury established deficit of ν_e from the sun
- Total solar flux measured by SNO agrees with prediction
- Super-K, K2K and MINOS have measured L/E form of ν_μ disapperance rate
- KamLAND have measured L/E form of reactor anti-ν_e disapperance rate

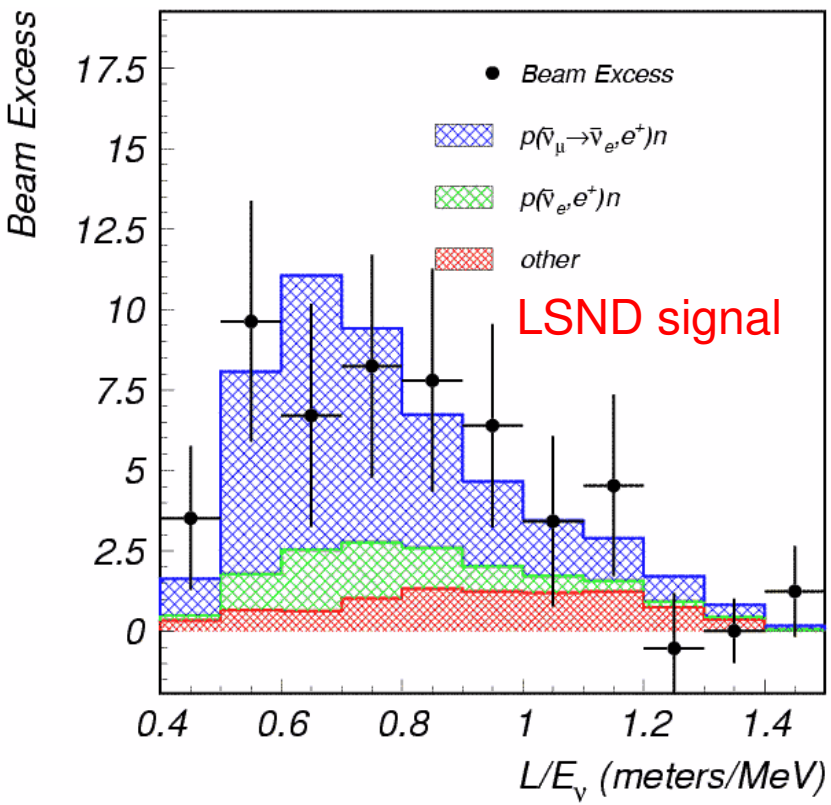


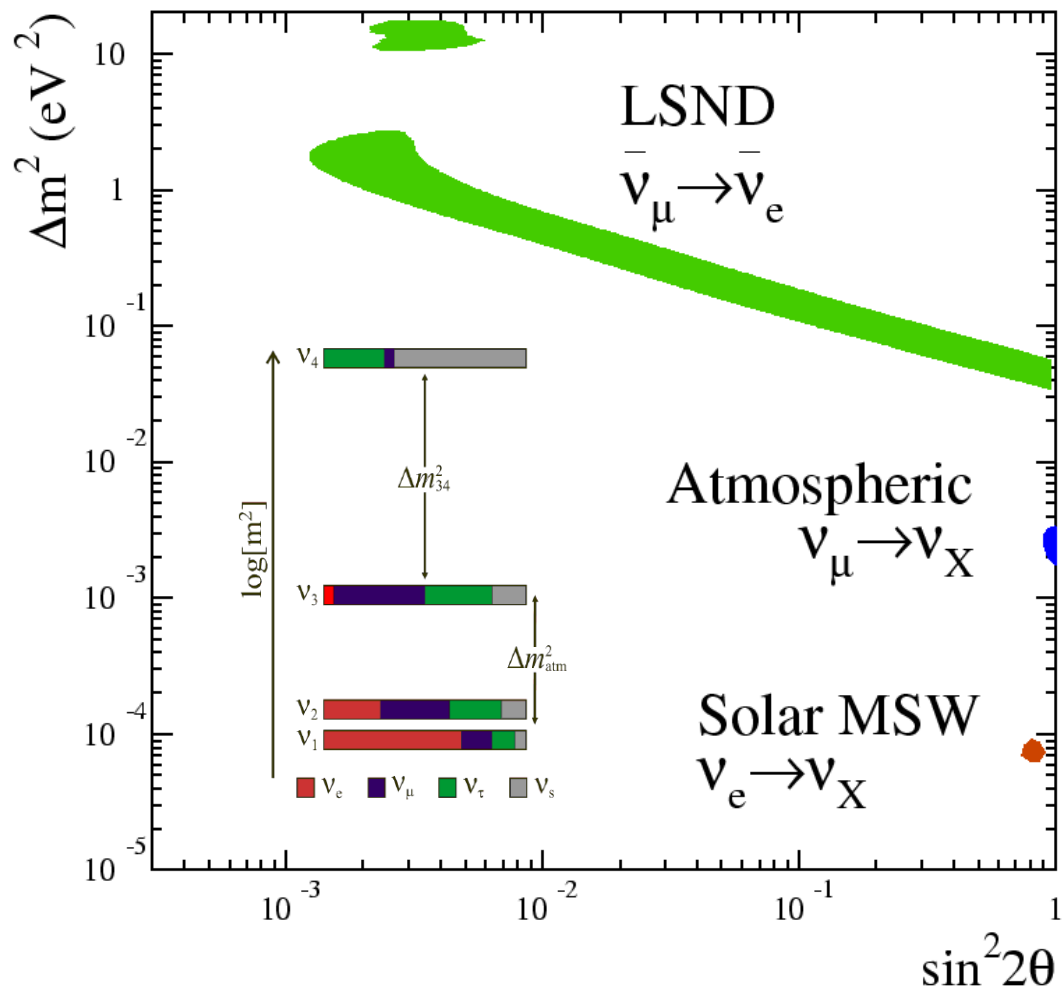


Neutrino oscillations: appearance

- Another signature of neutrino oscillation is apperance of "wrong" flavor neutrinos
- LNSD observes excess of anti-ν_e in anti-ν_μ beam:

  87.9 ± 22.4 ± 6.0 (3.8σ)

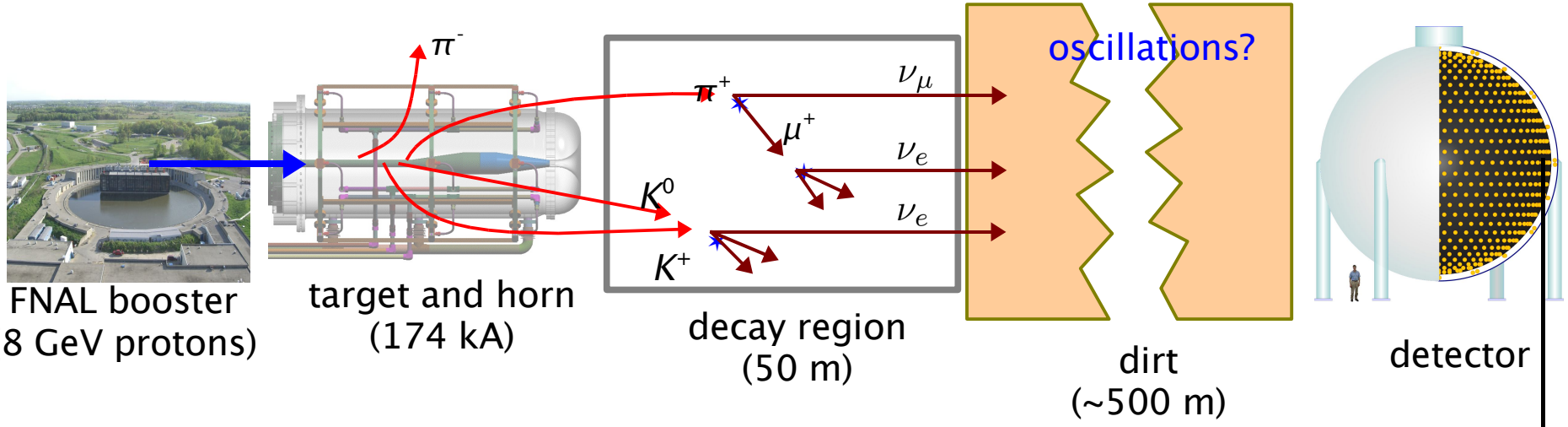




Mixing for two neutrino flavors

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

MiniBooNE searches for $\nu_\mu \rightarrow \nu_e$

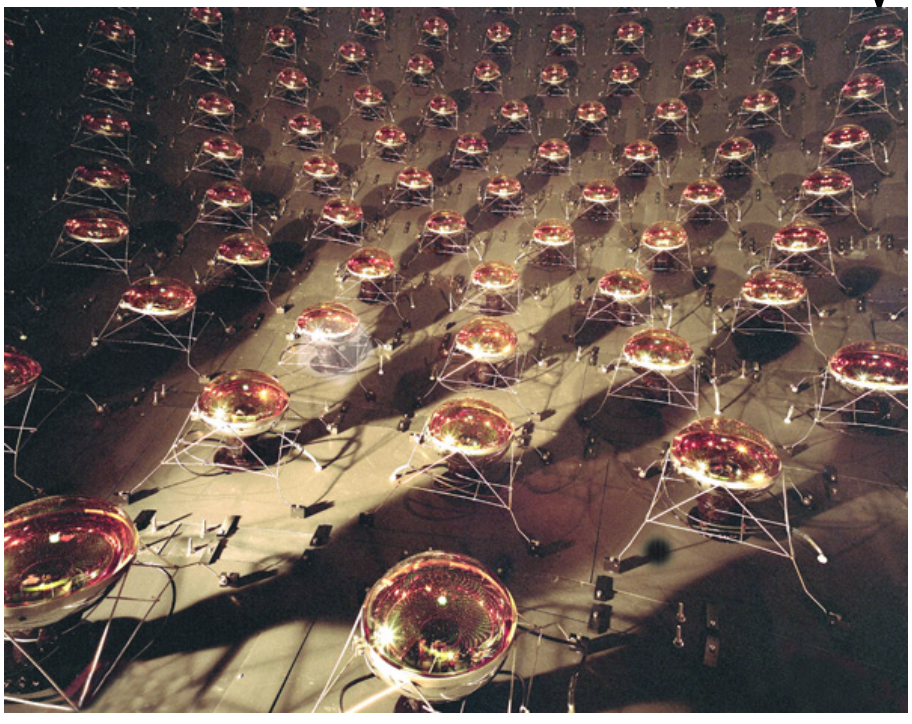


- 8GeV/c protons hit beryllium target
- 4×10^{12} protons/spill with up to 4Hz rate
- 174kA pulsed magnetic horn focuses positively charged hadrons: x6 flux gain
- Use neutrino beam to increase flux
- Pions decay to neutrinos with E≈0.8GeV
- Detector is 800 tons of mineral oil placed with L/E similar to LSND:

LSND: 0.03km/0.05GeV ~ 0.60 km/GeV

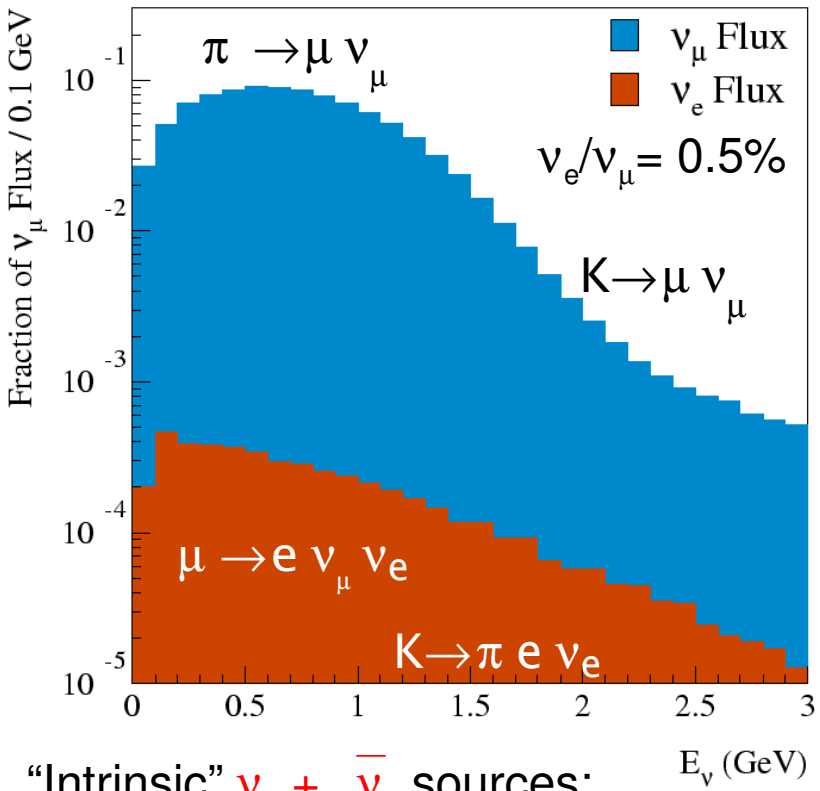
MiniBooNE: 0.50km/0.80GeV ~ 0.63 km/GeV

Inner tank: 1280 8" PMTS 10% coverage
Outer tank veto: 240 8" PMTs



MiniBooNE flux prediction

- HARP pion data were fit with Sanford-Wang parametrization: ~17% uncertainty
- Fit world kaon data in 10-24GeV using Feyman scaling: ~30% uncertainty
- Kaon flux is checked with off-axis "Little Muon Counter" and high energy events
- Geant4 simulation of beamline: target, horn, decay volume and absorber



"Intrinsic" ν_e + $\bar{\nu}_e$ sources:

$$\mu^+ \rightarrow e^+ \; \bar{\nu}_\mu \; \nu_e \quad (52\%)$$

$$K^+ \rightarrow \pi^0 \; e^+ \; \nu_e \quad (29\%)$$

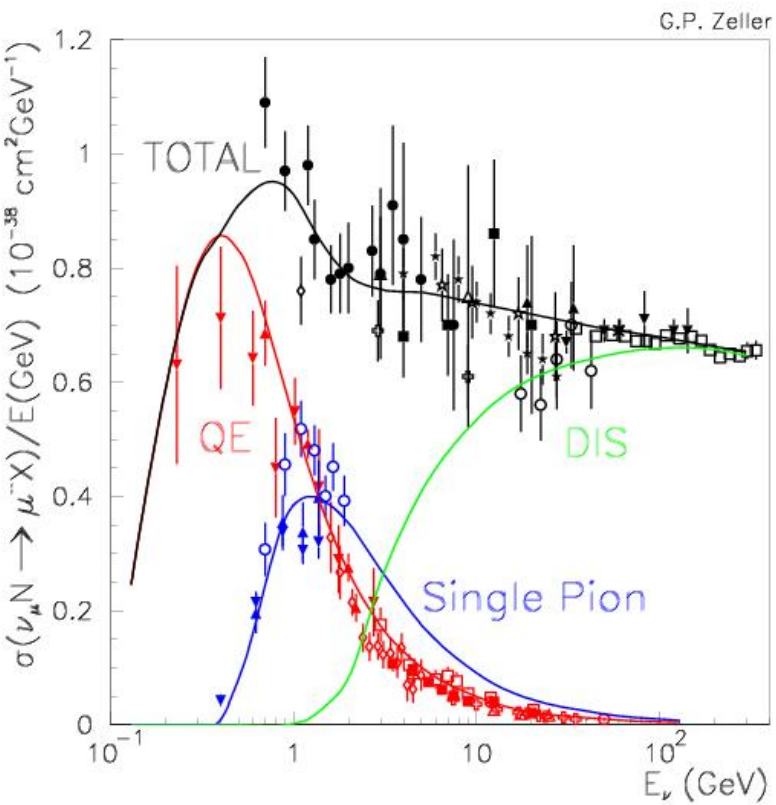
$$K^0 \rightarrow \pi \; e \; \nu_e \quad (14\%)$$

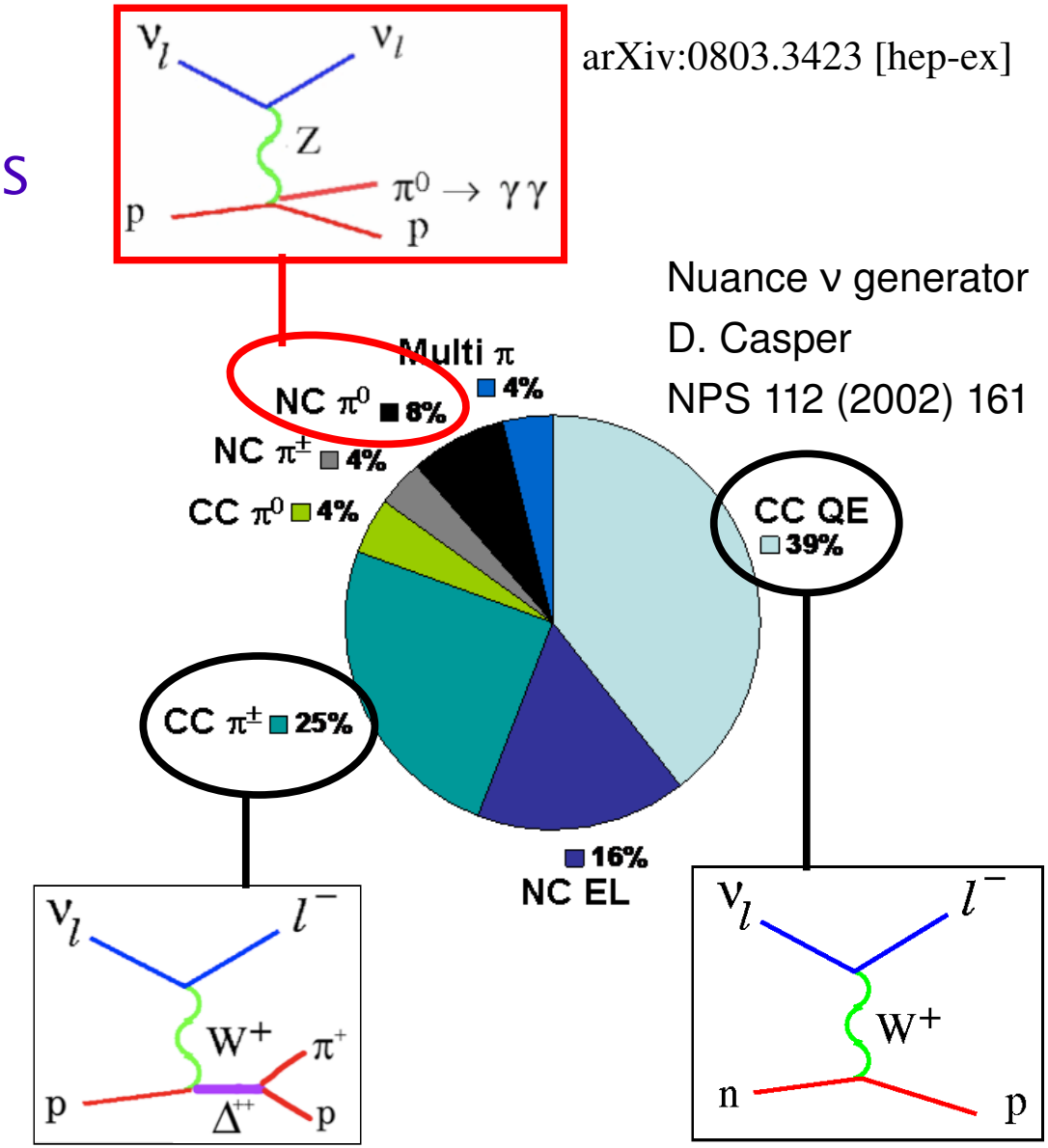
Other (5%)

Antineutrino content: 6%

MiniBooNE cross-section model

- Nuance is tuned to world ν data
- Same approach for Neugen/MINOS
- Monte-Carlo event rates are adjusted using MiniBooNE data outside signal region



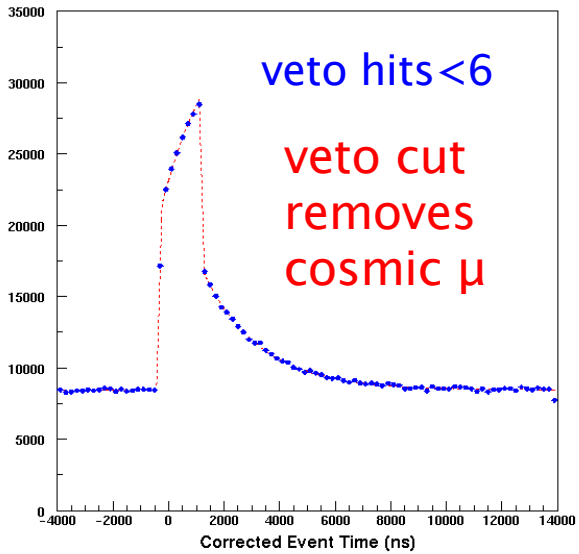


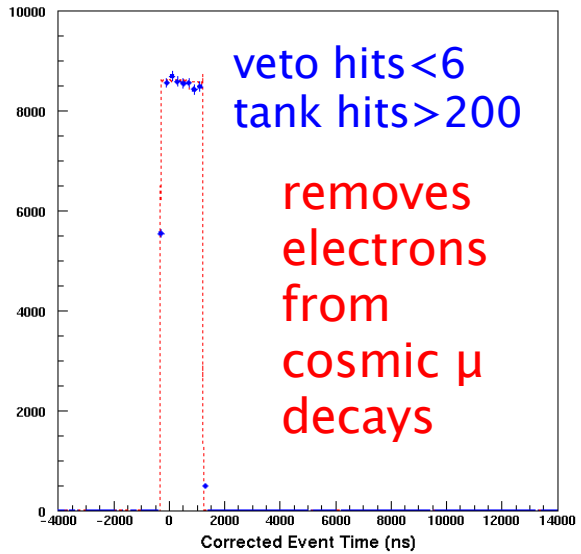
arXiv:0803.3423 [hep-ex]

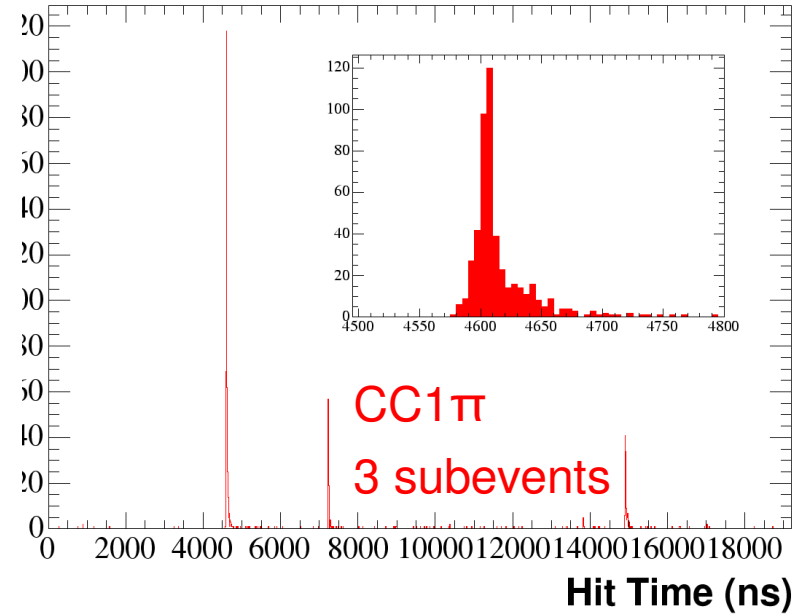
Nuance ν generator
D. Casper
NPS 112 (2002) 161

PRL 100, 032301 (2008).

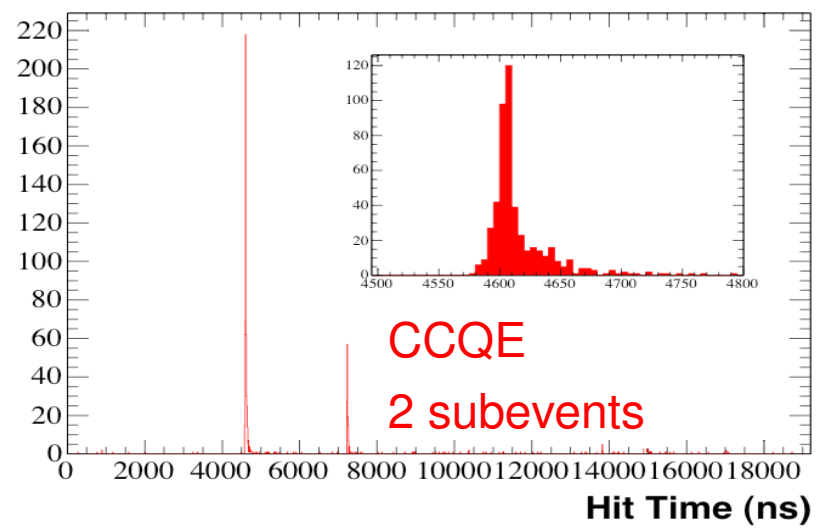
MiniBooNE beam events





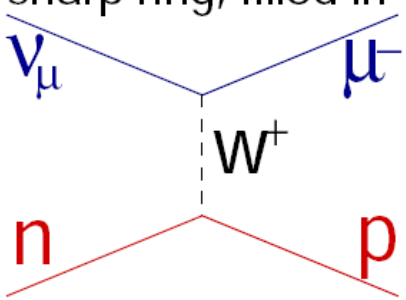


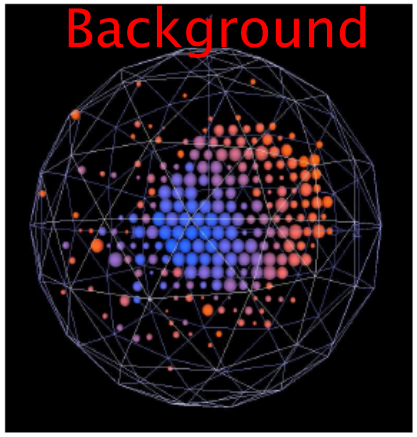
- PMTs collect scintillation and Cherenkov light
- Subvent is set of PMT hits close in time
- Select subevents within beam spill window
- Number of veto hits < 6
- Number of tank hits > 200
- Fiducial R < 500cm
- Only 1 subevent in spill window – removes CC1π and CCQE events



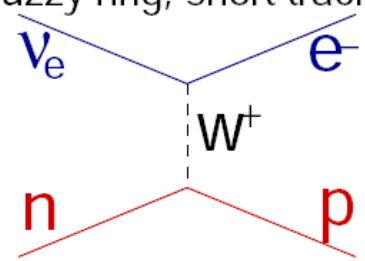
MiniBooNE ν_e selection: step 1

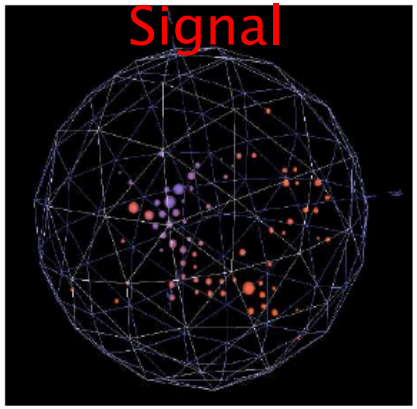
Muon candidate
sharp ring, filled in



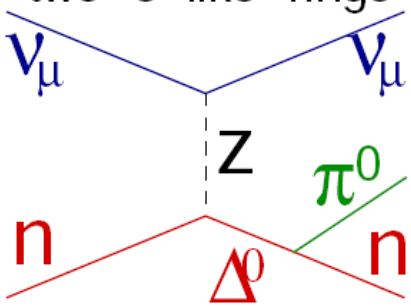


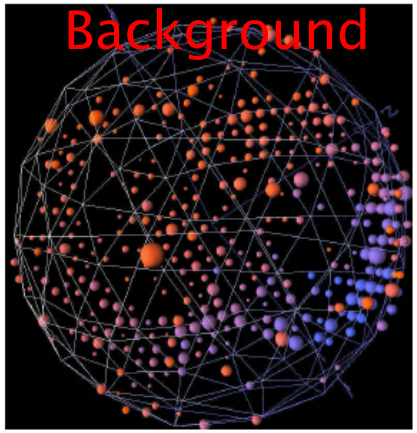
Electron candidate
fuzzy ring, short track

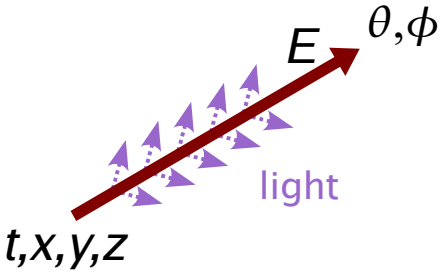




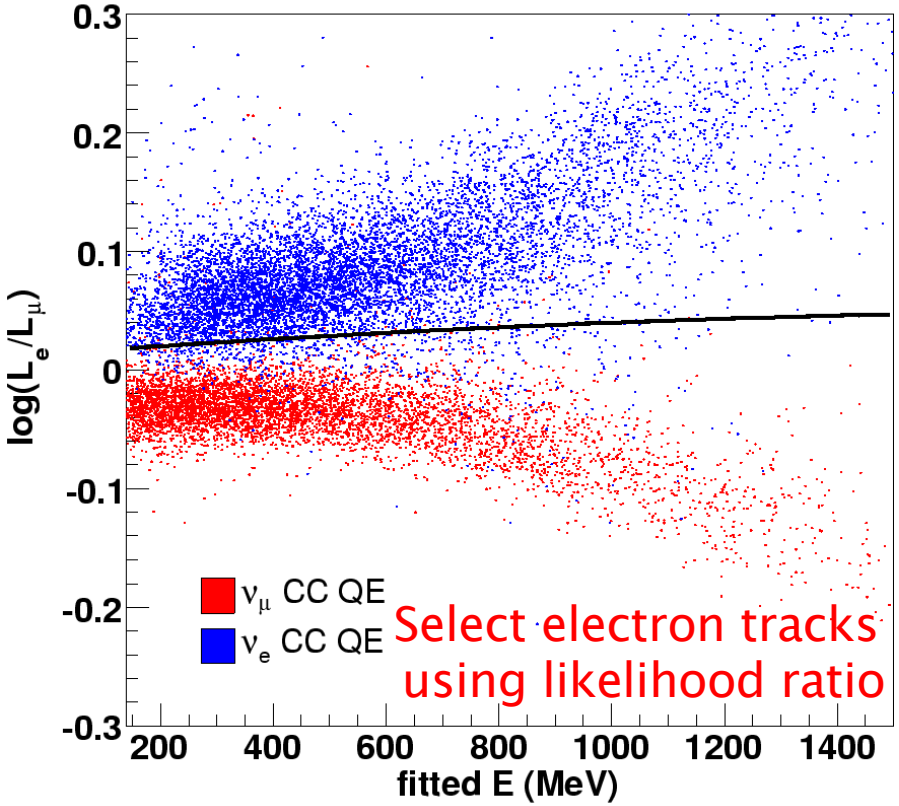
Pion candidate
two "e-like" rings







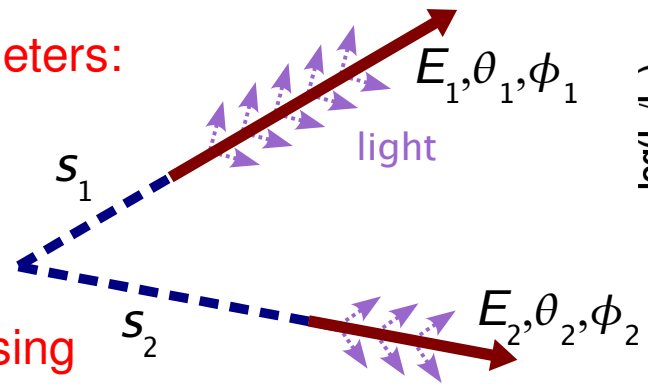
- Maximize likelihood of observed hits under 2 hypotheses:
  1) track is an electron
  2) track is a muon
- Vary 7 parameters

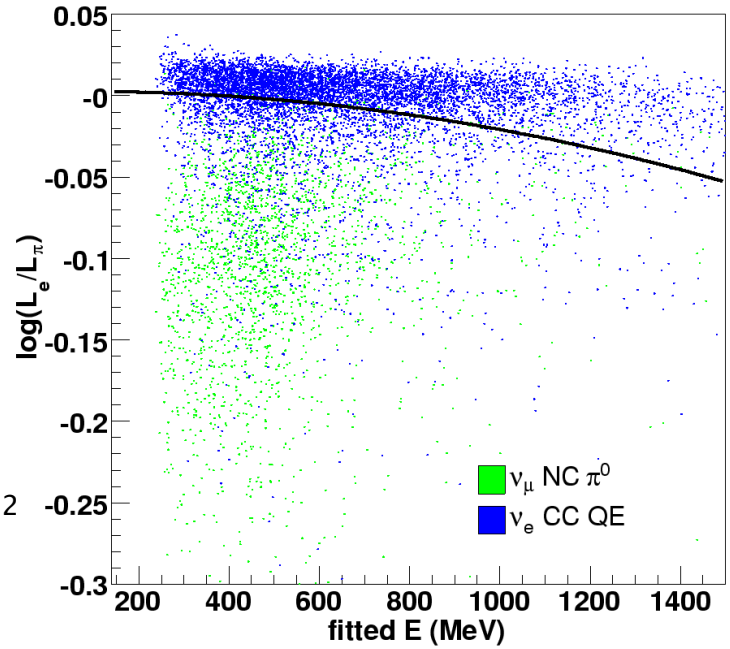


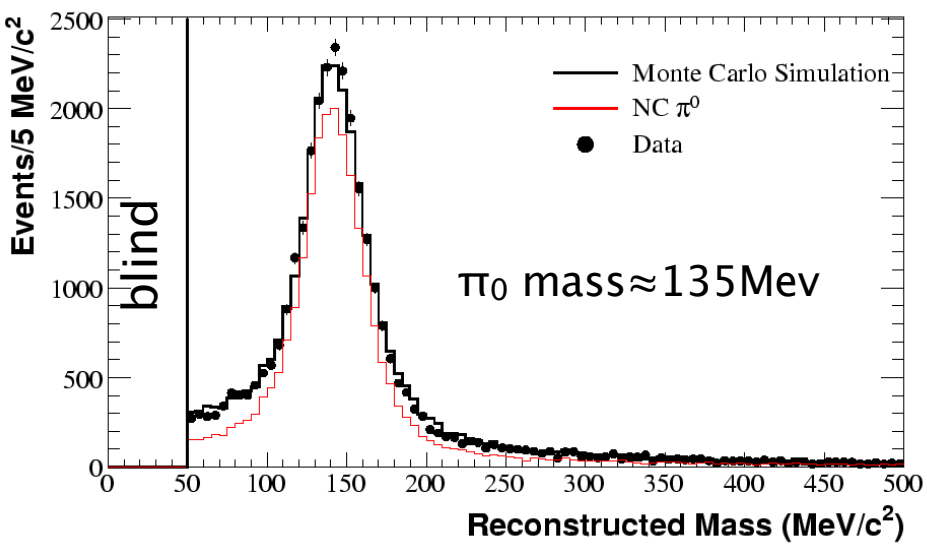
Select electron tracks using likelihood ratio

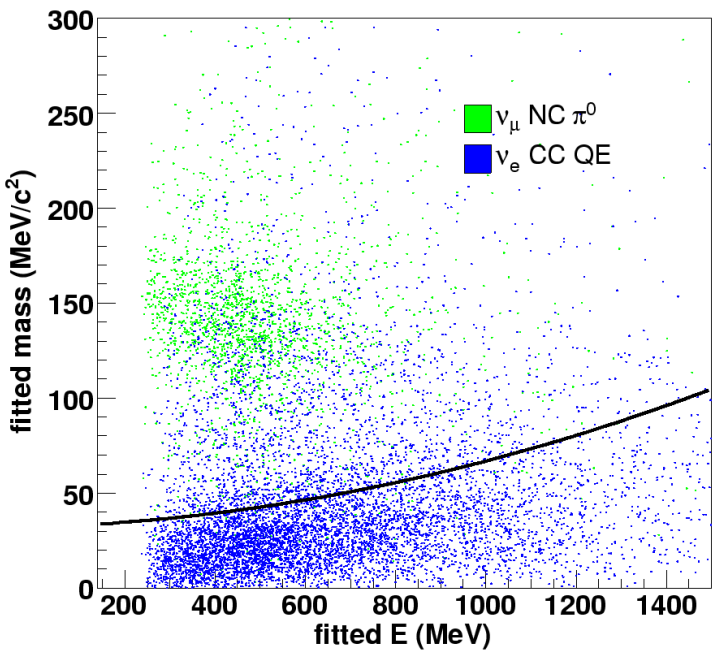
MiniBooNE ν_e selection: step 2

- Maximize likelihood of observed hits under 2 hypotheses with 10 parameters:
  1) event is electron
  2) event is $\pi^0 \rightarrow \gamma\gamma$
- Select electron events using likelihood ratios
- See C. Anderson talk in session T12

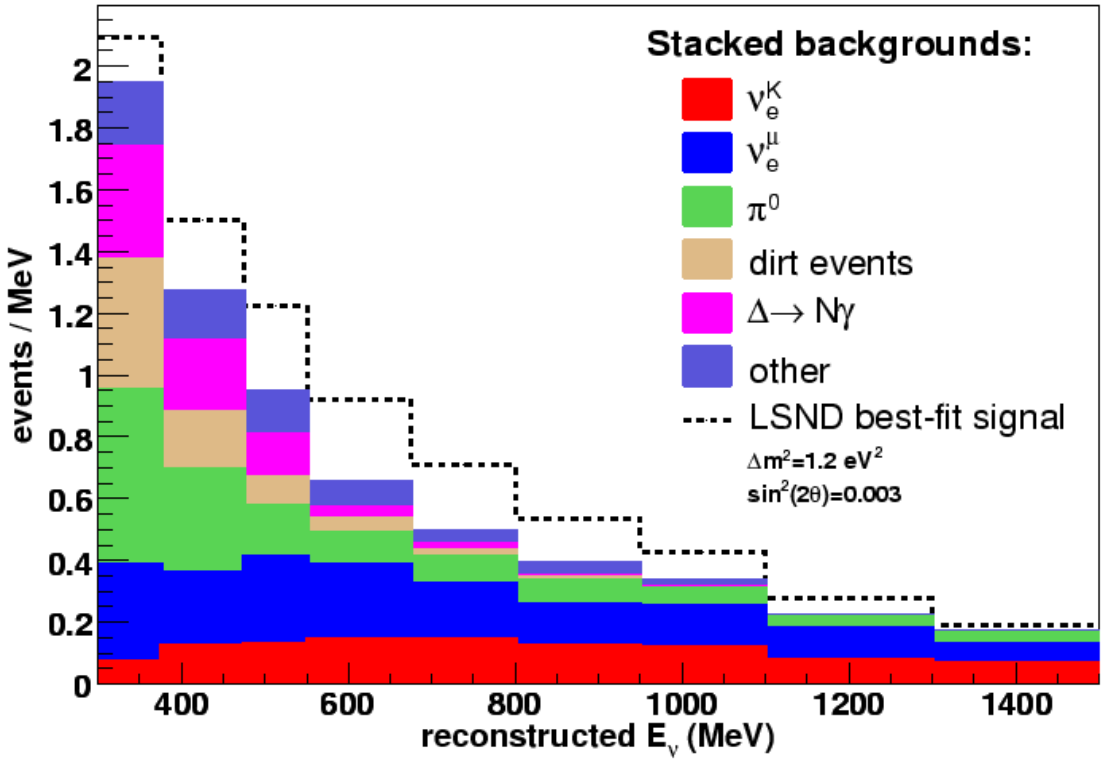








MiniBooNE ν_e signal prediction



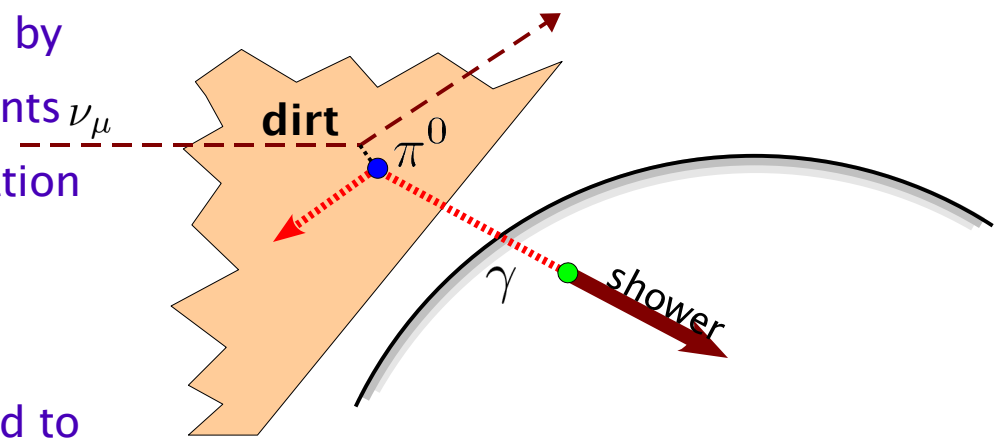
475 MeV – 1250 MeV

ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta \rightarrow N\gamma$	20
other	33
total	358

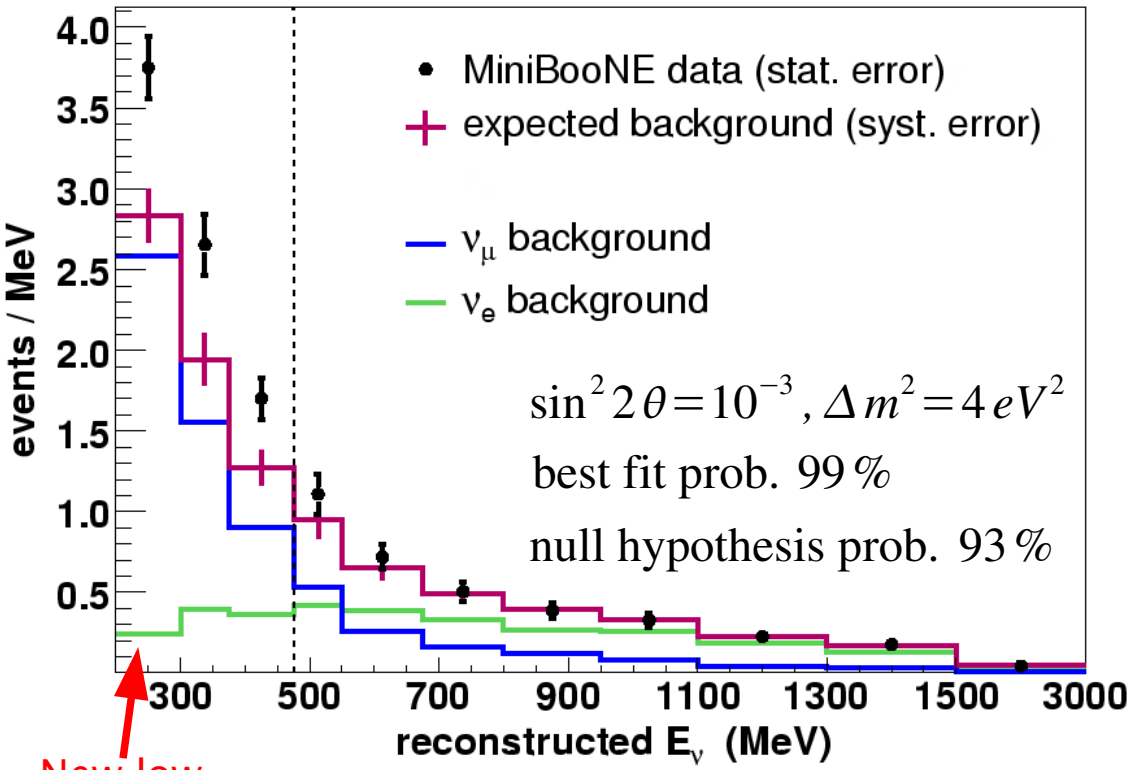
S/sqrt(B)=6.8

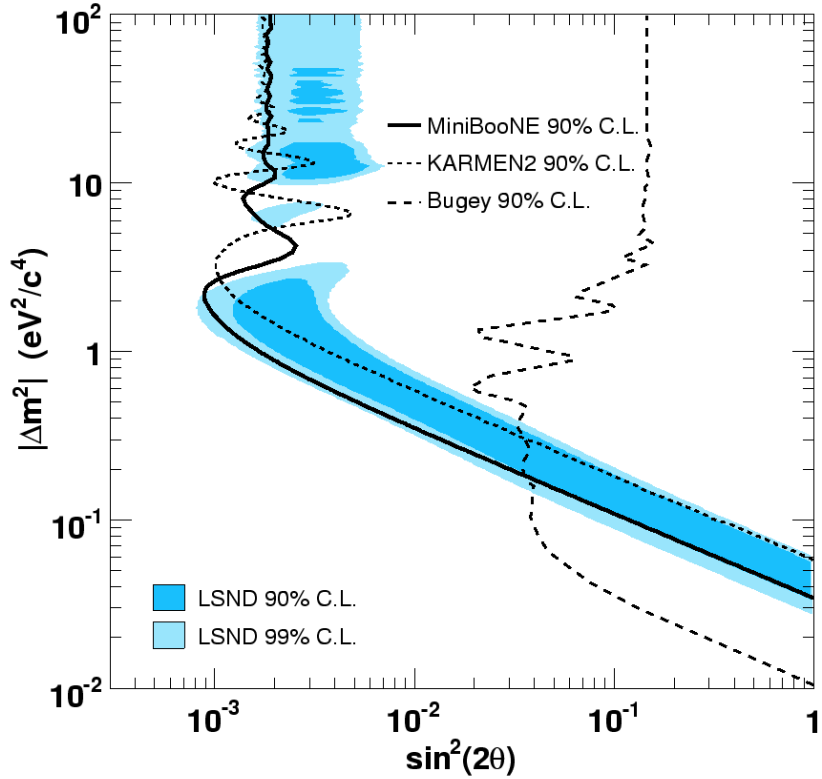
LSND best-fit $\nu_\mu \rightarrow \nu_e$ 126

- Blind analysis: signal box was opened in steps by gradually revealing more details about data events
- Event selection tuning and background estimation used events outside signal region
- "Bad" initial χ^2 for data and predicted visible energy (null and best fit): move energy threshold to 475MeV



MiniBooNE oscillation measurement





- Result is with 5.58×10^{20} protons
- No excess of ν_e events in expected signal region from LSND using
- Significance (stat + syst error):

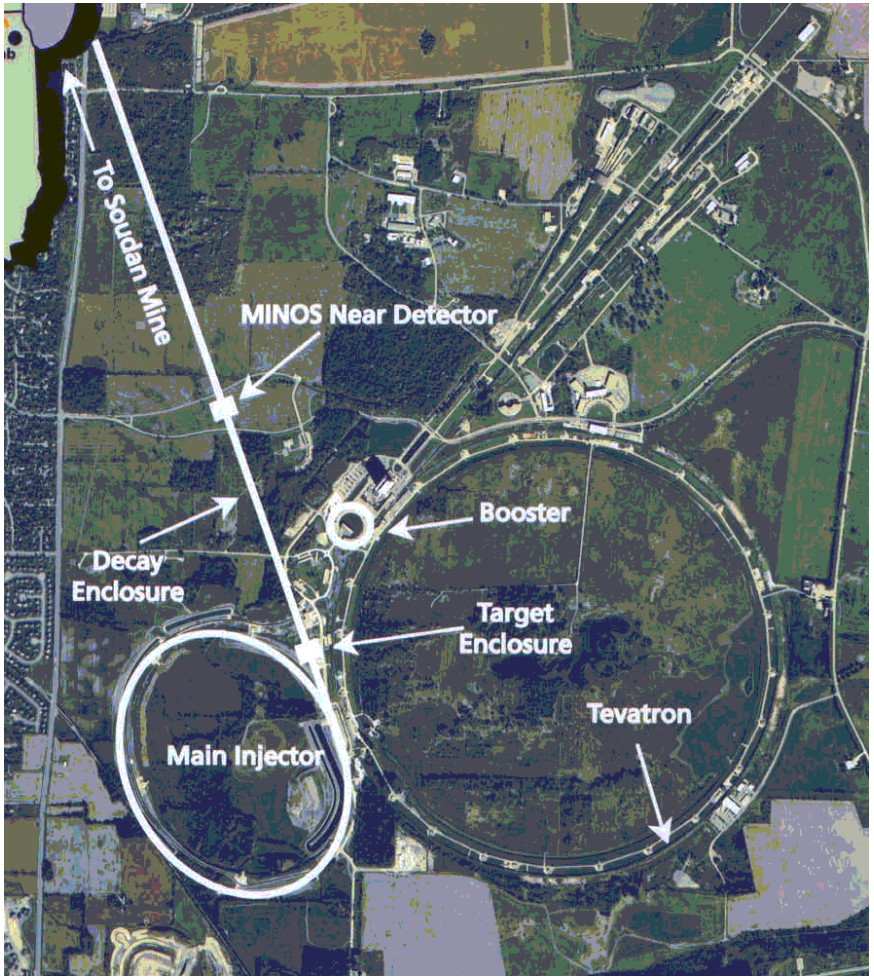
  475–1250 MeV: 22 ± 40
  300– 475 MeV: 95 ± 28
  200– 300 MeV: 91 ± 31

What does it all mean?

- LSND was wrong?
- Difference between ν_e and anti-ν_e?
- New physics that doesn't scale with L/E?
- Detector or flux effects?

Neutrinos at Main Injector (NuMI)

- Advance neutrino beamline uses 120GeV/c Main Injector protons
- 2.4×10^{13} protons/spill every ~2.4s
- 0.2 MW average beam power

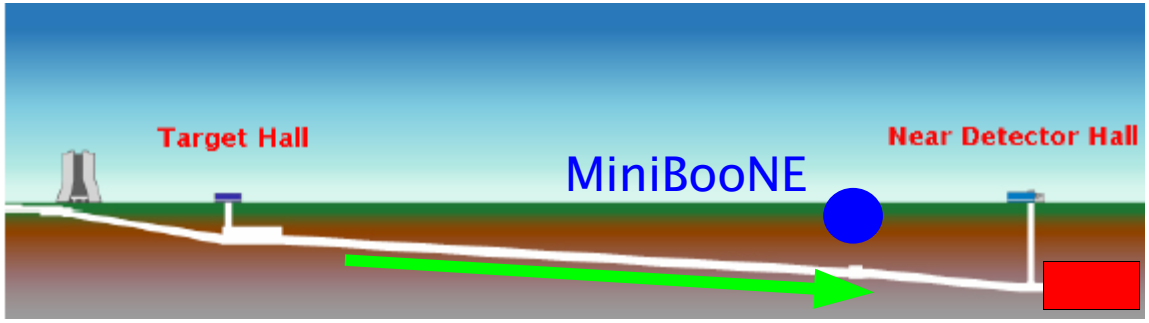


MiniBooNE is 110 mrad off-axis:

$$\nu_\mu = 81\%, \bar{\nu}_\mu = 13\%, \nu_e + \bar{\nu}_e = 6\%$$

MINOS ND is on-axis:

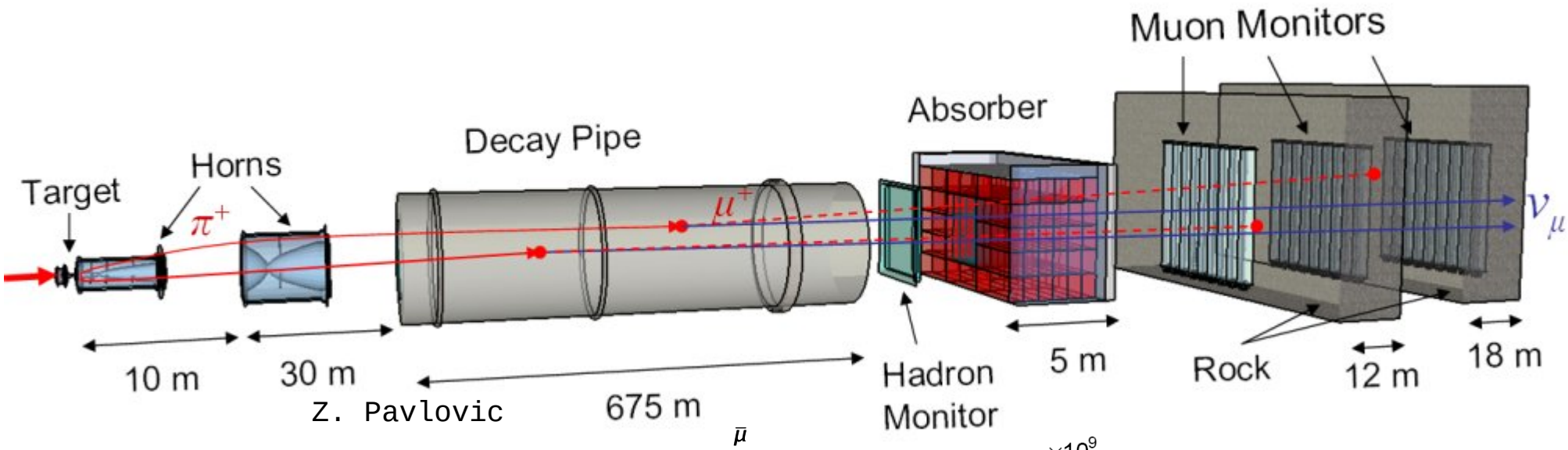
$$\nu_\mu = 93\%, \bar{\nu}_\mu = 6\%, \nu_e + \bar{\nu}_e = 1\%$$



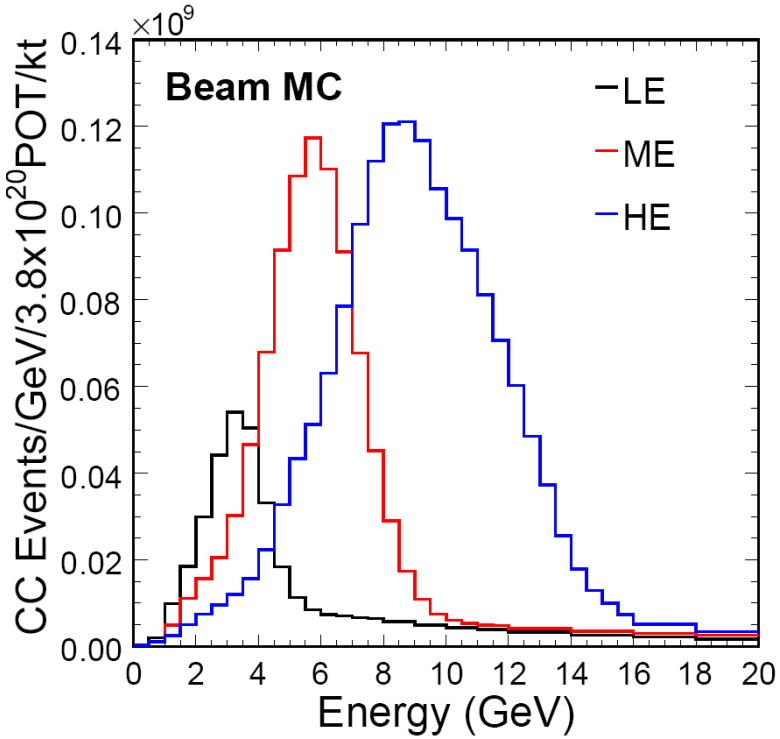
ν beam direction

MINOS near detector

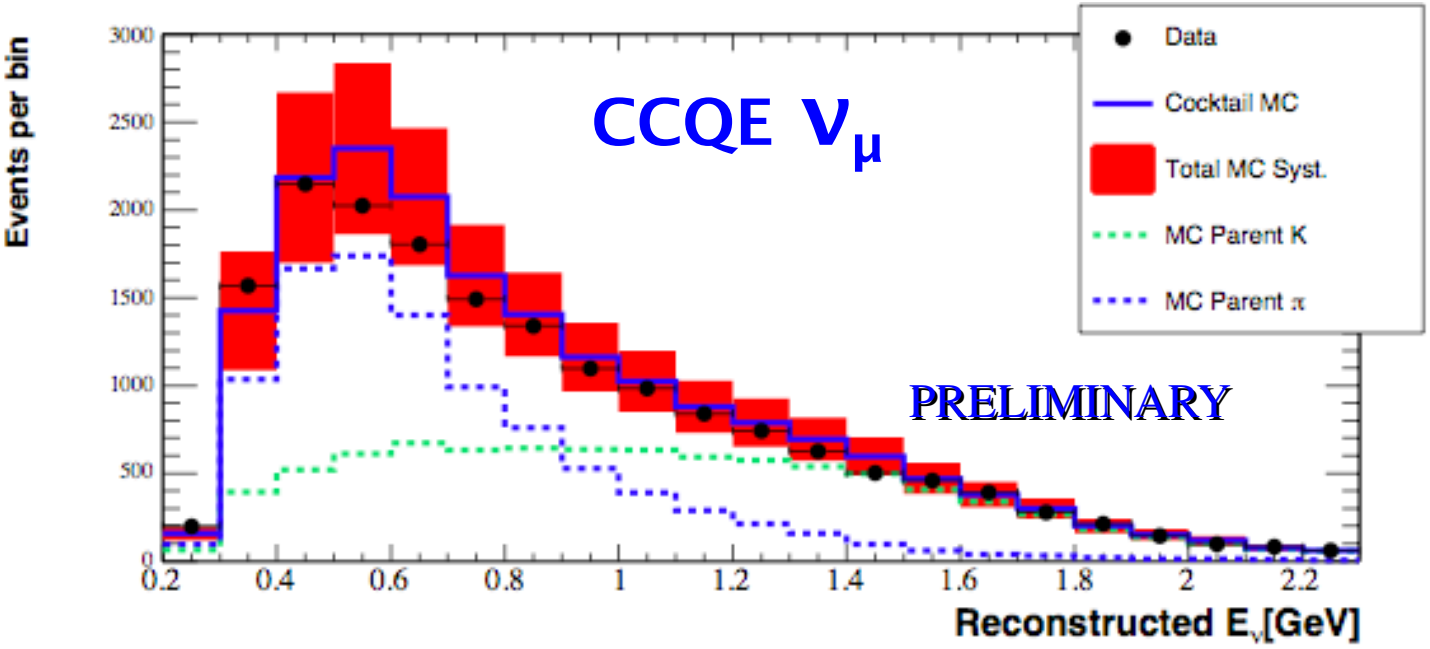
NuMI beamline

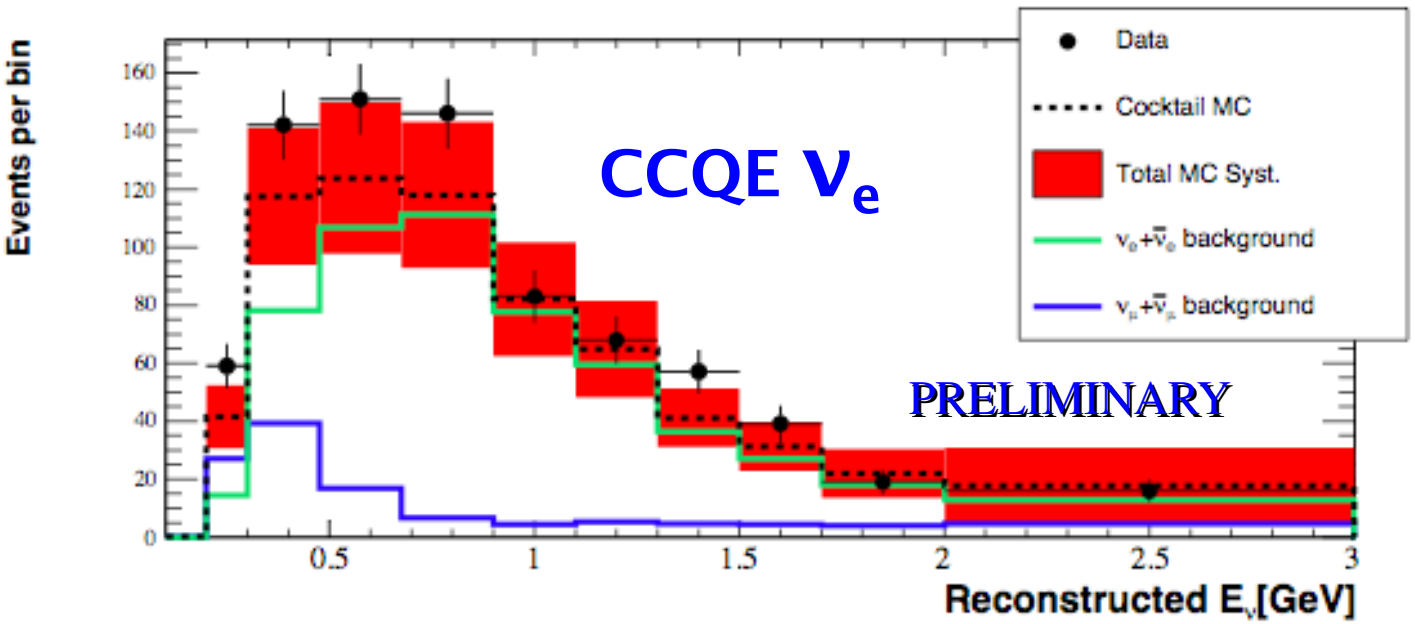


- Water cooled graphite target
- 2 pulsed parabolic magnetic horns
- Hadron and muon monitors
- Change beam flux by changing relative positions of target and horns
- Mostly run in Low Energy (LE) beam
- See talks by L. Loiacono in T12 and J. Chvojka in R13 about using muon monitors for flux measurement



NuMI events at MiniBooNE





- Similar selection as for oscillation analysis
- Excess of low energy ν_e but within syst. error
- Systematic errors can be reduced with more work
- Can rule out problems with ν_e cross-sections and π^0 and dirt backgrounds
- See talk by Z. Djurcic in T12

MiniBooNE summary and outlook

- MiniBooNE does not observe ν_e apperance signal in expected energy region if LSND signal scales as L/E

- A significant excess of low energy ν_e is under investigation with significant update later this year:
  - Improved analysis with 15-20% more data
  - Refined hadronic and flux models

- MiniBooNE accumulated 2×10^{20} protons in anti-neutrino mode and is approved to run for 2 more years
  - New cross-section measurements
  - Partial covererage of LSND anti-neutrino signal region

- Working on additional cross-section results and ν_μ disappearance analysis with SciBooNE as near detector

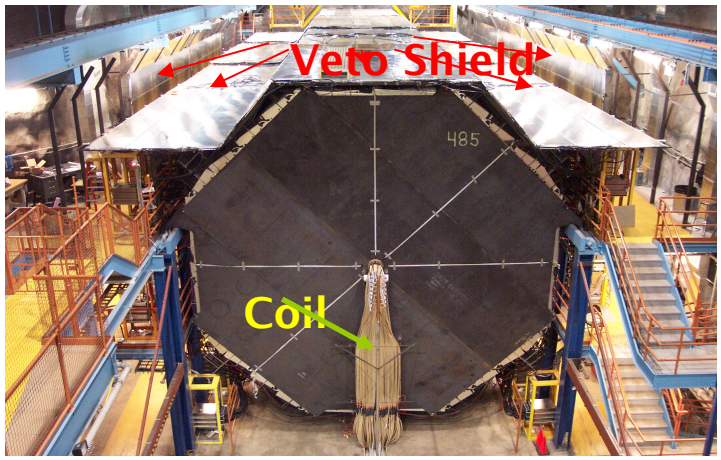
Main Injector Neutrino Oscillation Search (MINOS)

- Investigate oscillations with high intensity ν_μ beam
- Measure ν_μ and anti-ν_μ disappearance
- Search for $\nu_\mu \rightarrow \nu_e$ appearance
- Search for $\nu_\mu \rightarrow \nu_s$ transition
- Cosmic ray and neutrino cross-section physics

Near Detector

Two functionally identical magnetized iron-scintillator calorimeters

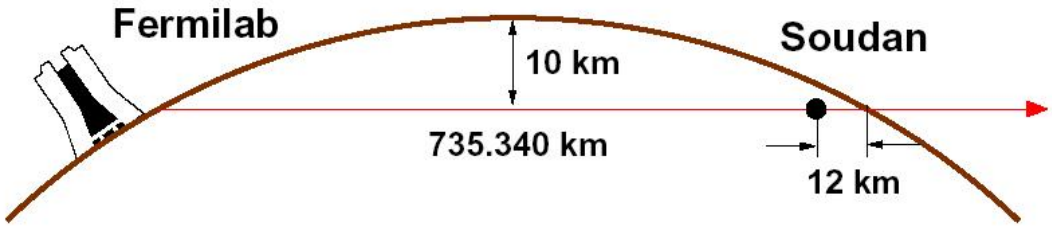
Far Detector



980 tons

1 km from target

100 m deep



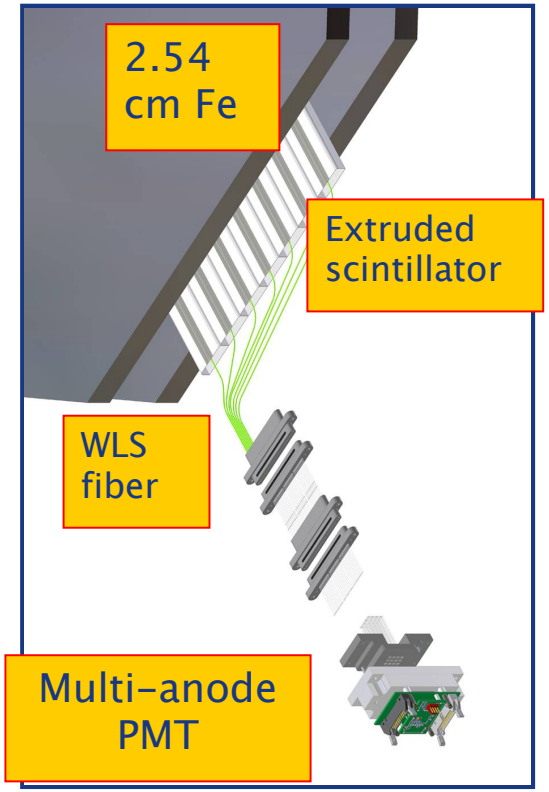
5400 tons

735 km away

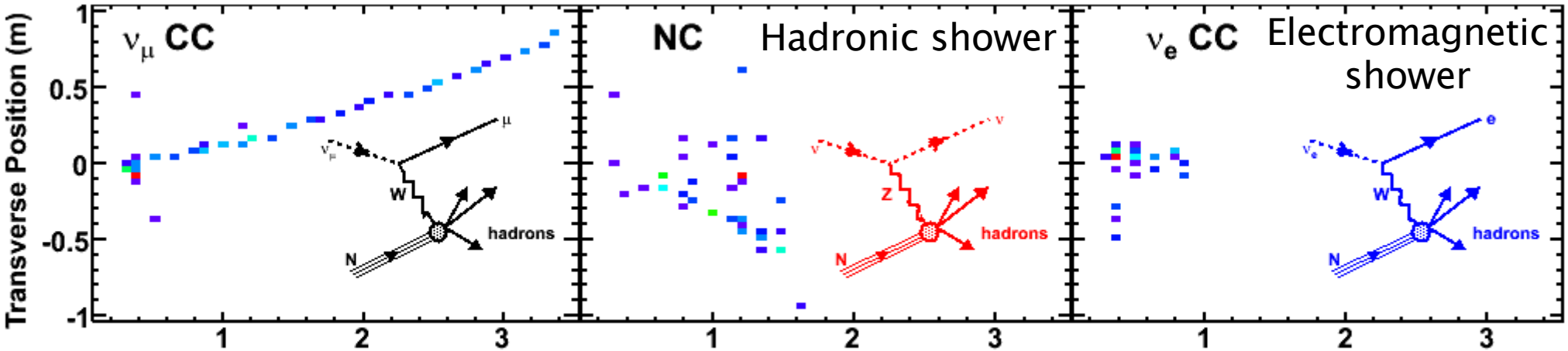
700 m deep

MINOS detectors

- MINOS uses far/near ratio to reduced errors
- Two detectors use same steel and scintillator
- Toroidal magnetic field with ~1.2T
- Shower energy = sum of scintillation light
- Muon momentum = range or curvature
- For calibration overview see talk by J. Kim in R13



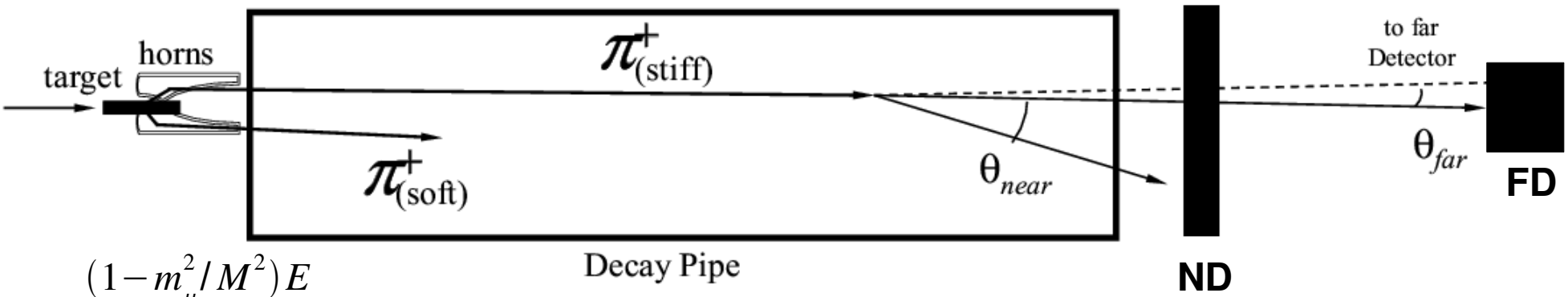
Select events using number of steel planes crossed, hit pattern and hit pulse height



μ track and hadronic shower

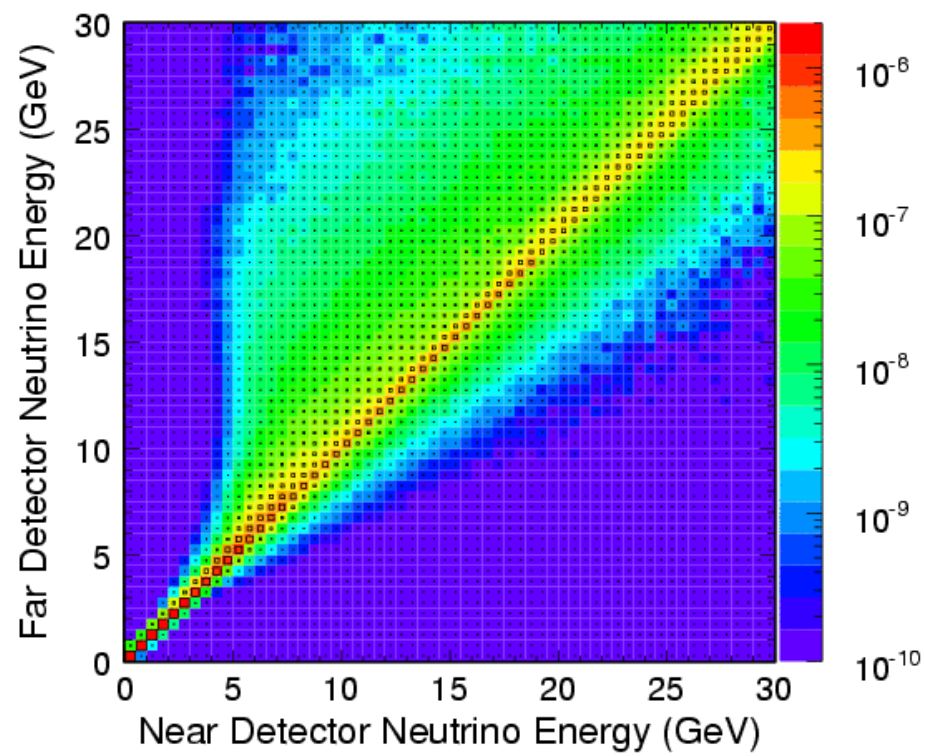
Near to far extrapollation

Rely on relativistic kinematics of pion and kaon decays to project near detector observed spectra to far detector



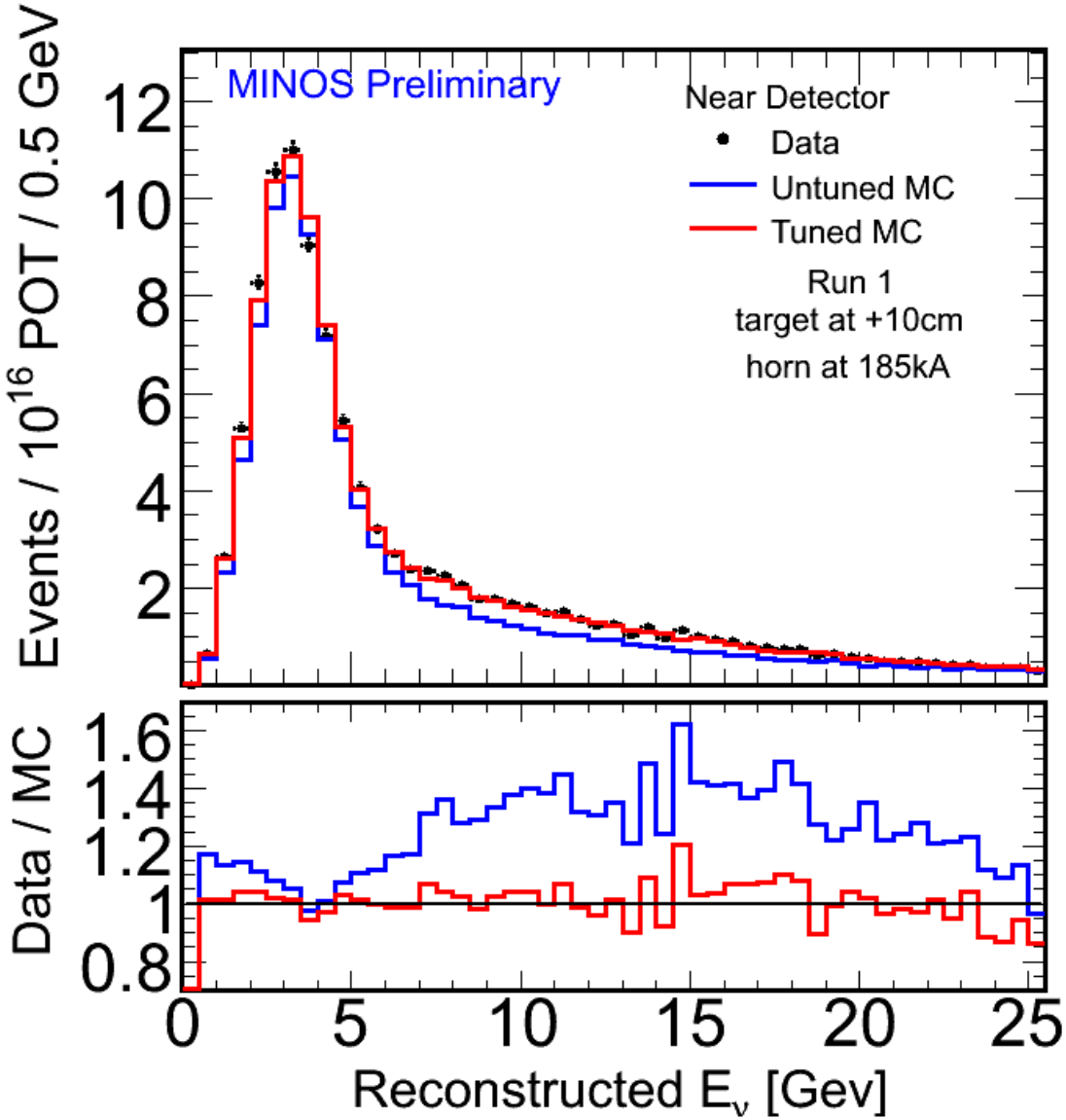
$$E_\nu = \frac{(1 - m_\mu^2 / M^2) E}{1 + \gamma^2 \tan^2 \theta_\nu^2}$$

- Use near detector data to extrapolate near spectra to far detector
- MC provides acceptance, purity and energy smearing corrections
- Using near detector data reduces systematic errors from flux and cross-section uncertainties

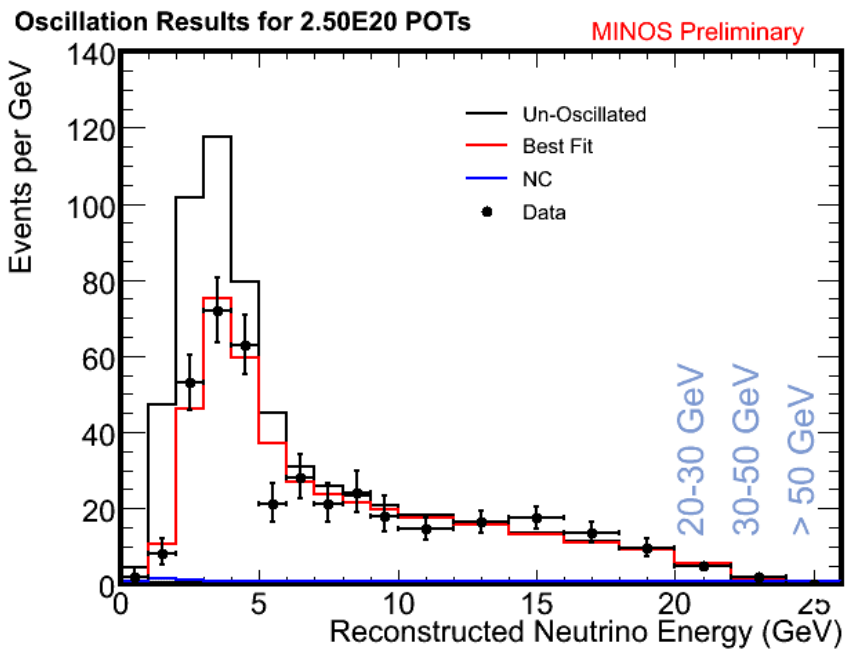


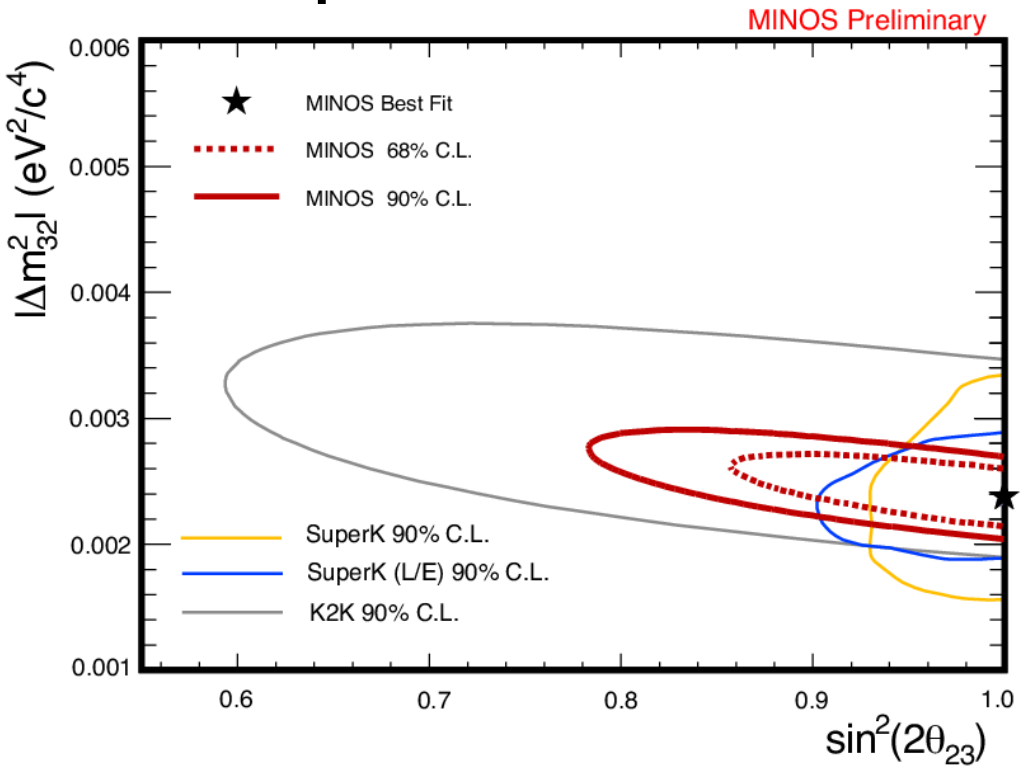
Near detector: CCν_μ events

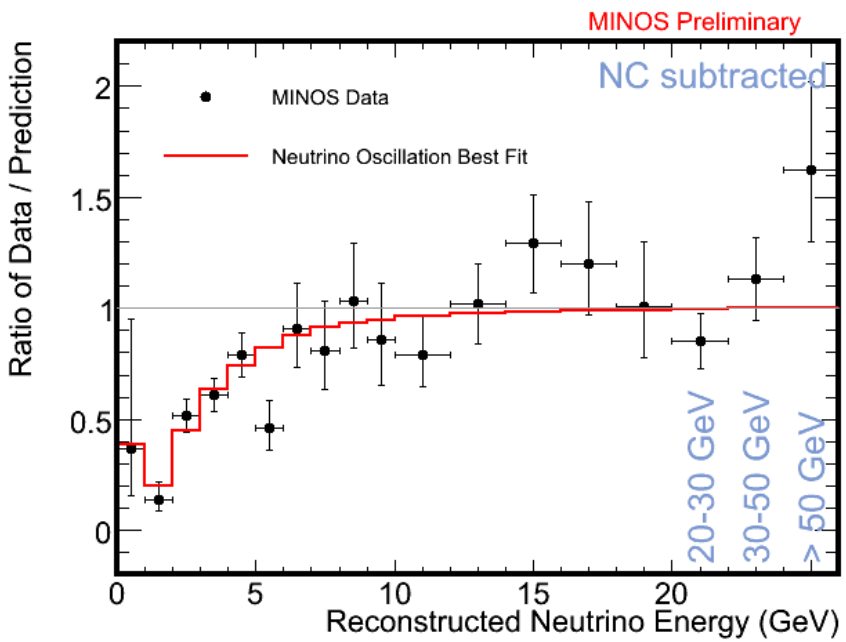
- Form CC event selection variable using 7 variables
- ~1% NC background
- Similar algorithm in two detectors
- Tune MC using data from 7 different beam configurations
- Tuning has small effect on predicted far detector spectra
- See talk by R. Armstrong in R13



Far detector: CCν_μ events







$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27\,\Delta m^2 L/E)$$

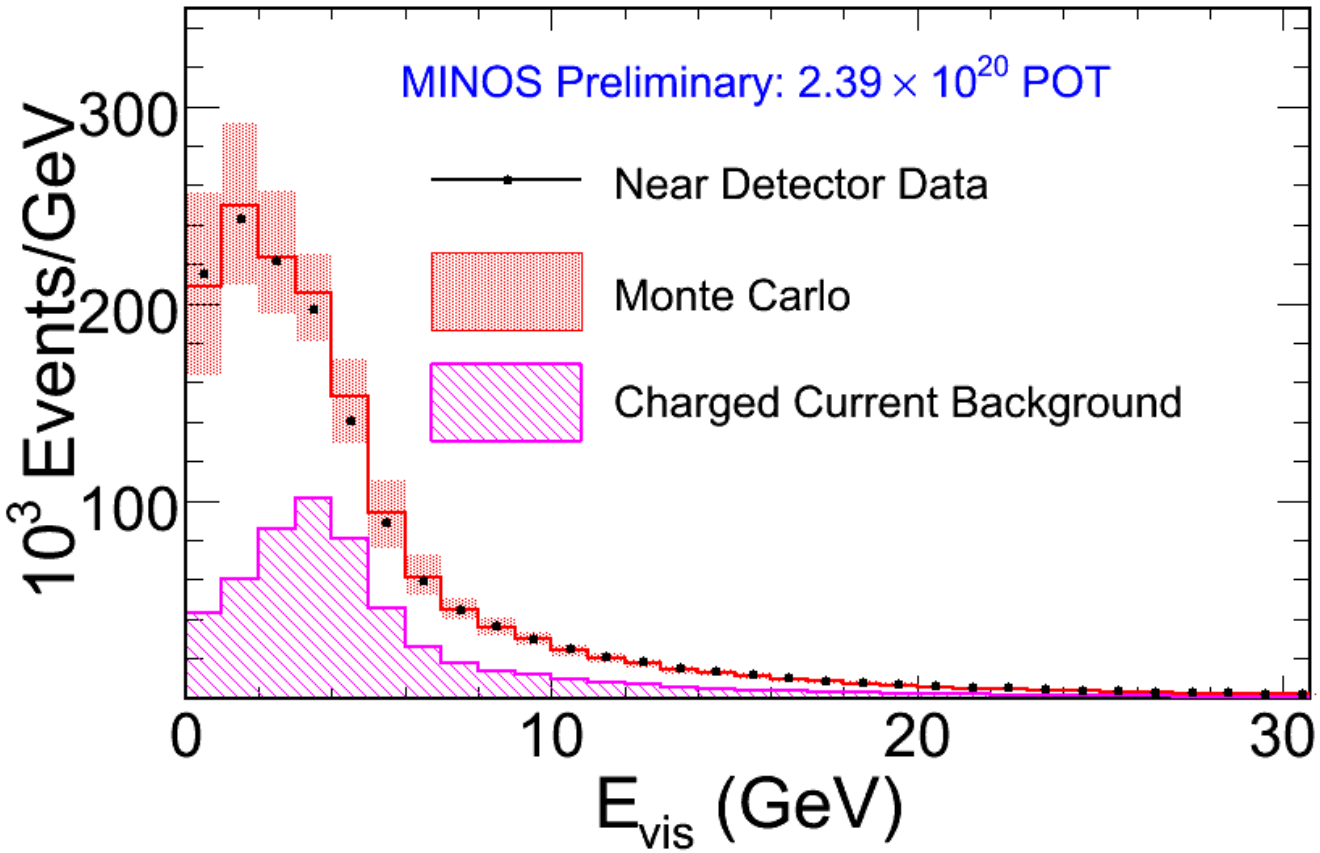
$$|\Delta m_{32}| = 2.38^{+0.20}_{-0.16}\,(\text{stat} + \text{syst}) \times 10^{-3}\,eV^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.08}\,(\text{stat} + \text{syst})$$

Best fit: $\chi^2/ndf = 41.2/34 = 1.2$

Null: $\chi^2/ndf = 139.2/36 = 3.9$

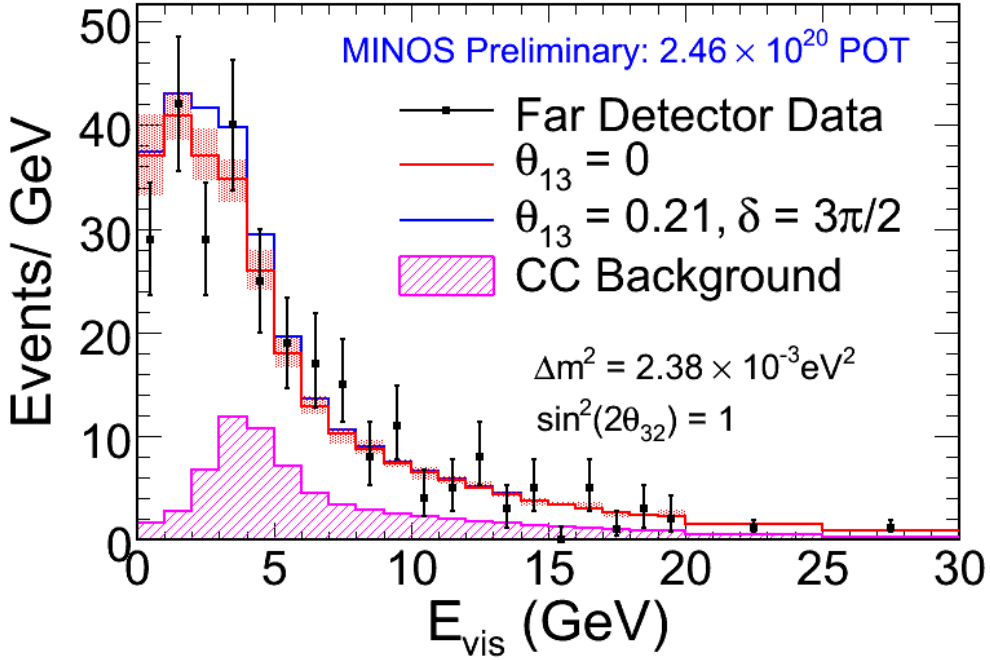
Near detector: NC events



- Cleaning cut: no overlapping events in time and space
- NC events: short events without clear muon track
- CC background is checked using data from different beam configurations: 15% uncertainty

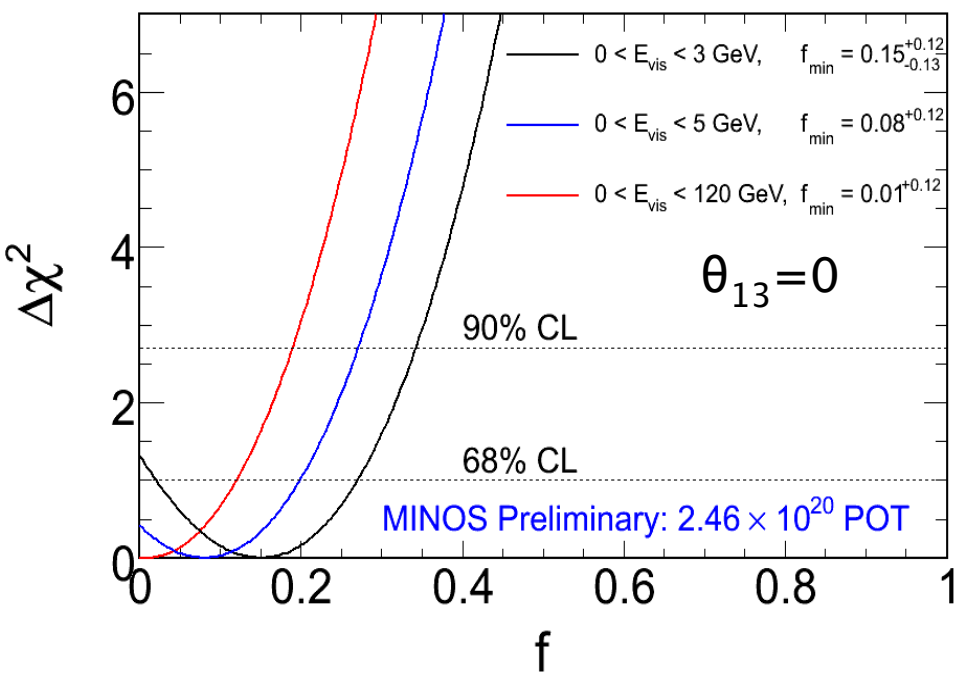
- Good data/MC agreement for visible energy of NC-like events
- Systematic error includes calibration error, hadronization, intranuclear rescattering, flux and selection uncertainties

Far detector: NC events

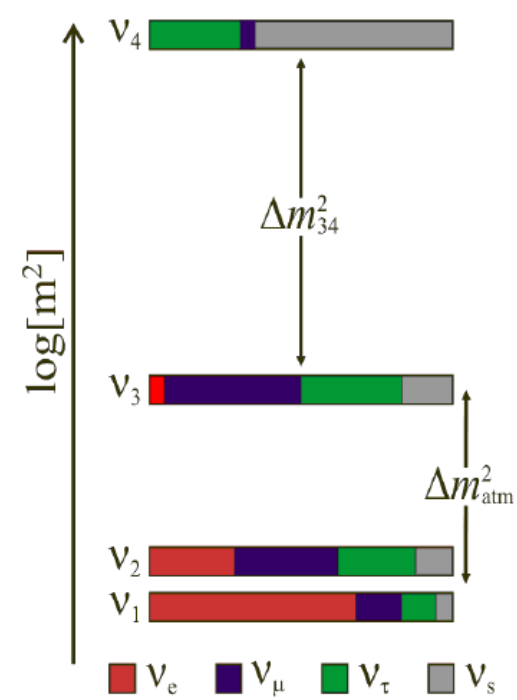


$$N_{\text{expected}} = NC(1-f) + CC\,\nu_\mu + CC\,\nu_e + CC\,\nu_\tau$$

- Fit energy spectrum for f
- ν_e and ν_τ are classified as NC by this analysis
- Expect at most ~20 electron events at CHOOZ limit and ~5 tau events

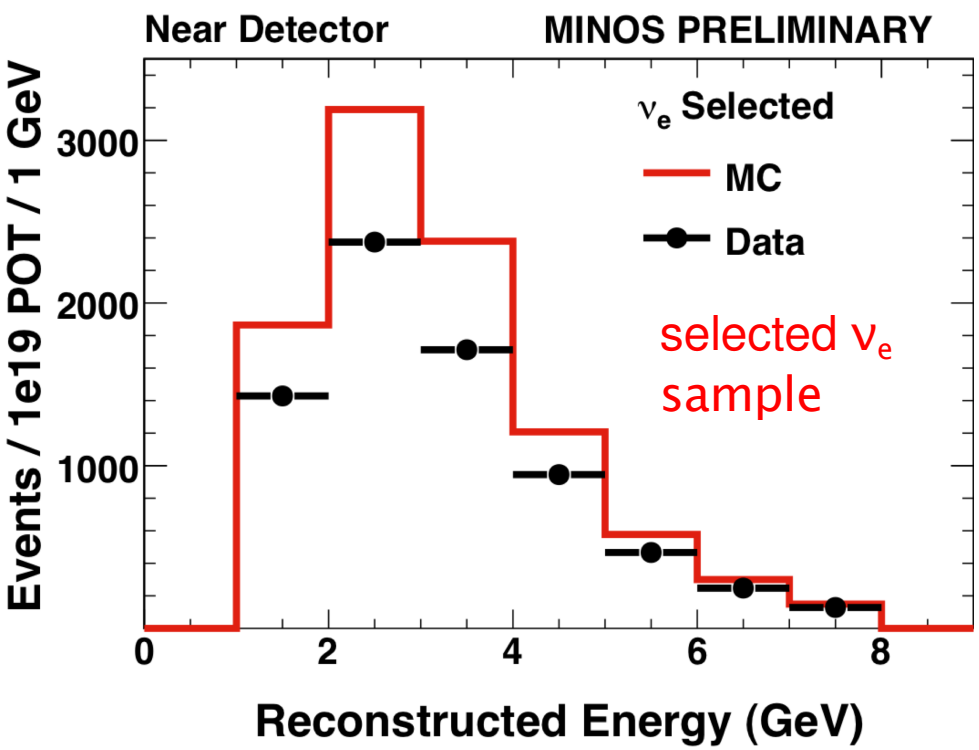


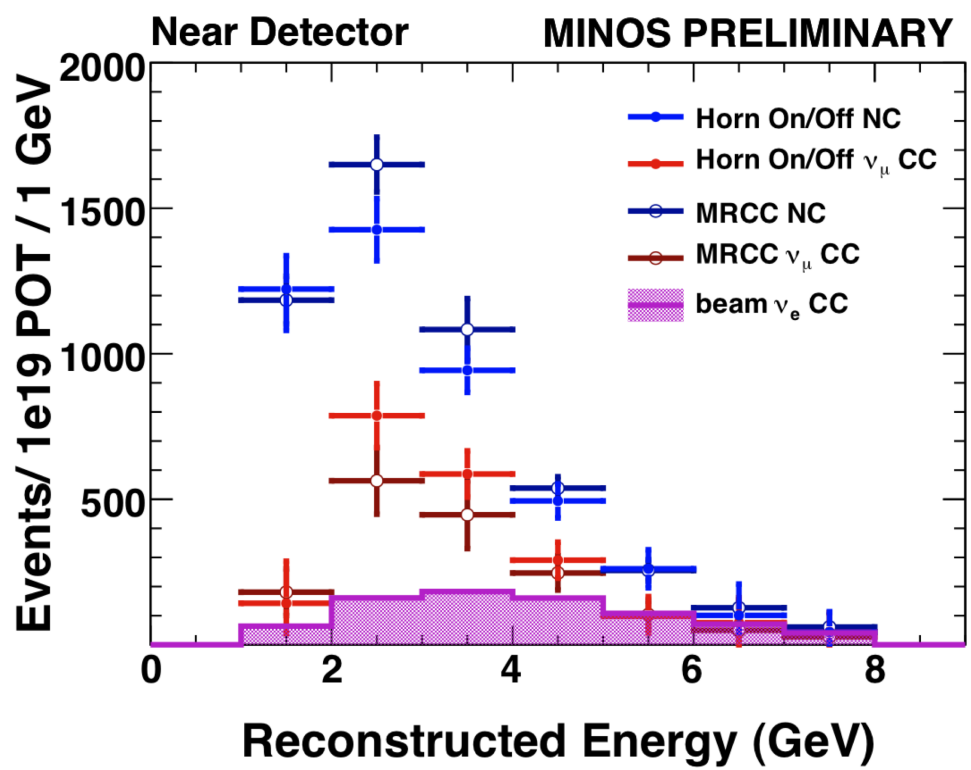
$$\chi^2 = \frac{(N_{data} - N_{MC})^2}{N_{MC} + \sigma^2_{sys}}$$



MINOS ν_e appearance search

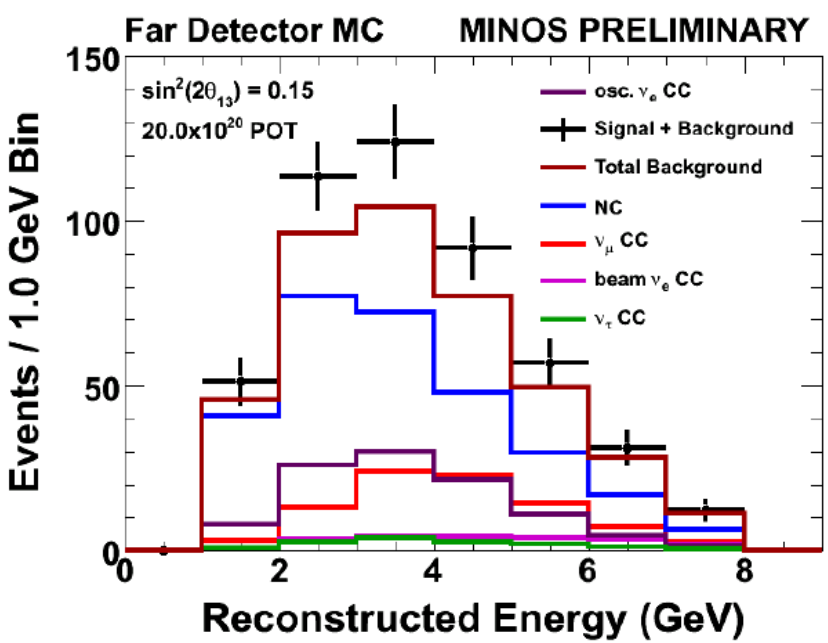
- Search for far detector ν_e apperance in initially 99% ν_μ beam
- Select ν_e with neural net based algorithm (T. Yang in R13)
- Selected near detector events are mostly CCν_μ and NC
- Selection depends on details of hadronic simulation
- Solution: use two independent data driven methods to estimate NC and CCν_μ backgrounds (G. Pawloski in F1)

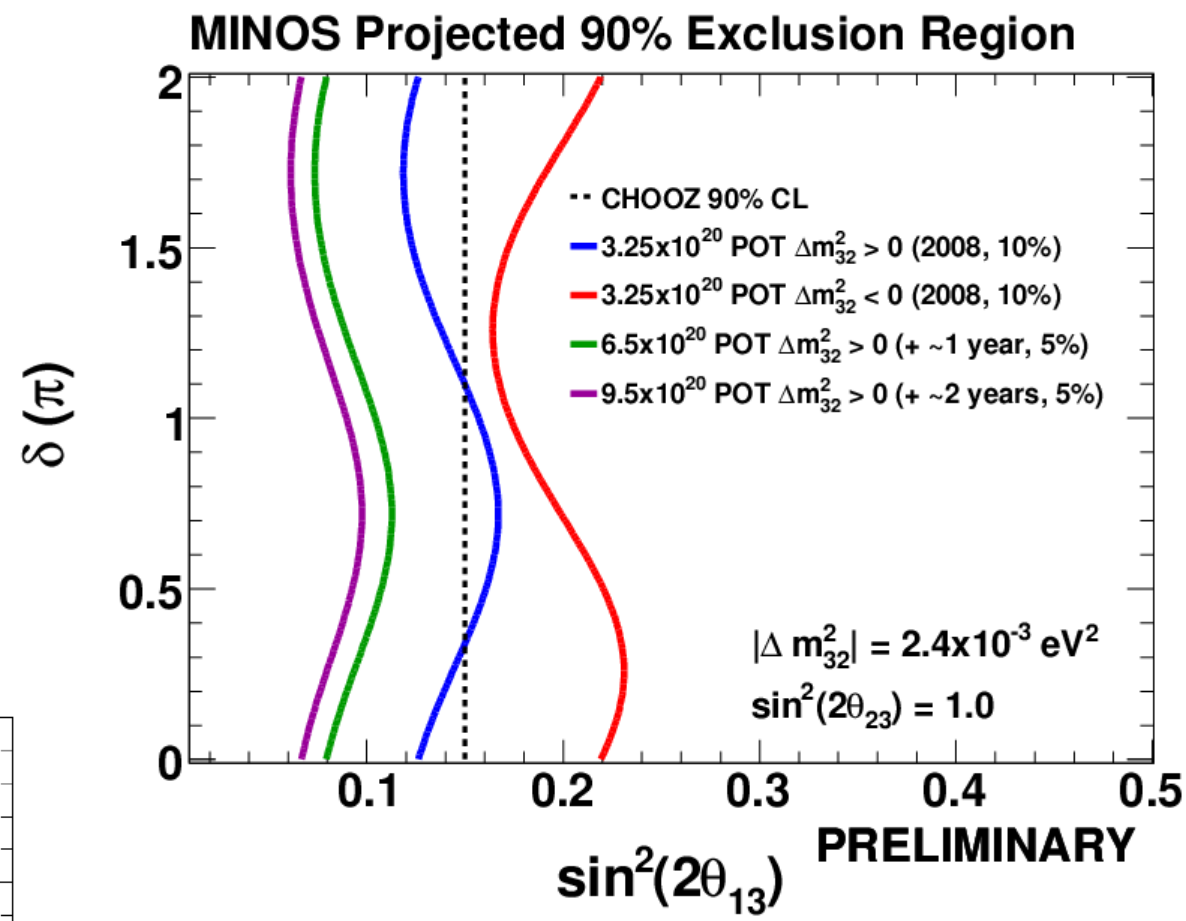




MINOS ν_e sensitivity

- Projected limits shown with current and expected MINOS exposure (J. Boehm in T12)
- At CHOOZ limit expect 12 ν_e signal events and 42 background events with 3.25×10^{20} protons





- Use sidebands to study predicted far detector backgrounds
- Expect first result later this year

MINOS summary and outlook

- The analysis of 2.5×10^{20} protons is complete and the results are consistent with standard oscillation picture:

$$\left|\Delta m_{32}\right| = 2.38^{+0.20}_{-0.16}(\text{stat} + \text{syst}) \times 10^{-3}\, eV^2$$

$$\sin^2 2\theta_{23} = 1.00_{-0.08}(\text{stat} + \text{syst})$$

$$E_{vis} < 3\,\text{GeV} : \text{fraction of disappearing NC events} < 0.35 \text{ at } 90\,\%\, CL$$

- Expect new results with 3.25×10^{20} protons for ν_μ and anti-ν_μ disappearance and ν_e appearance search later this year

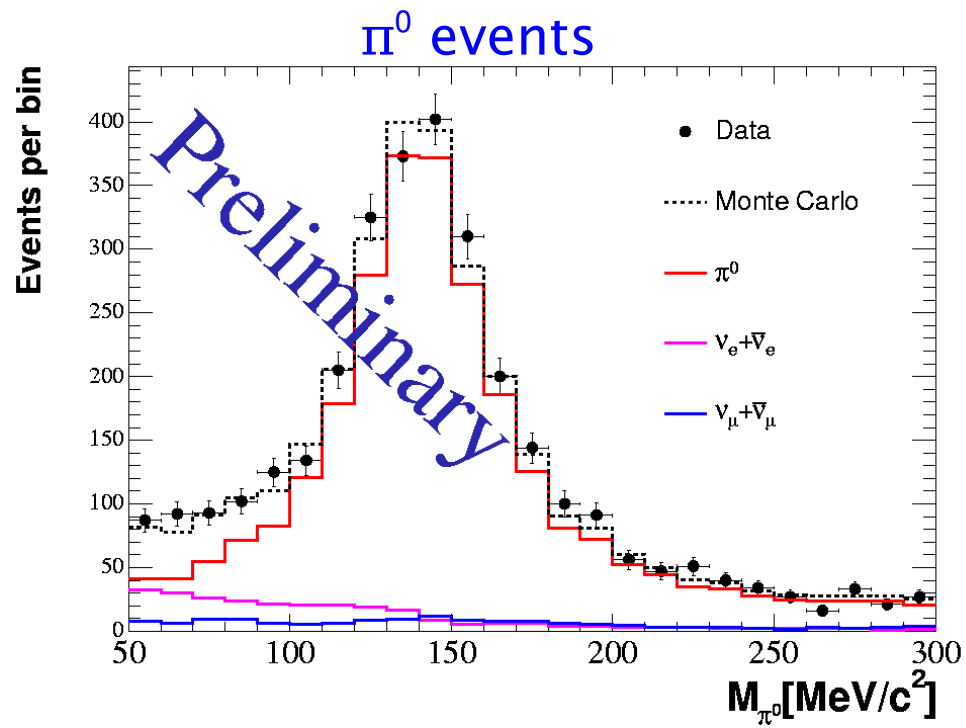
- Accumulating data and hope for $>6 \times 10^{20}$ by next Spring

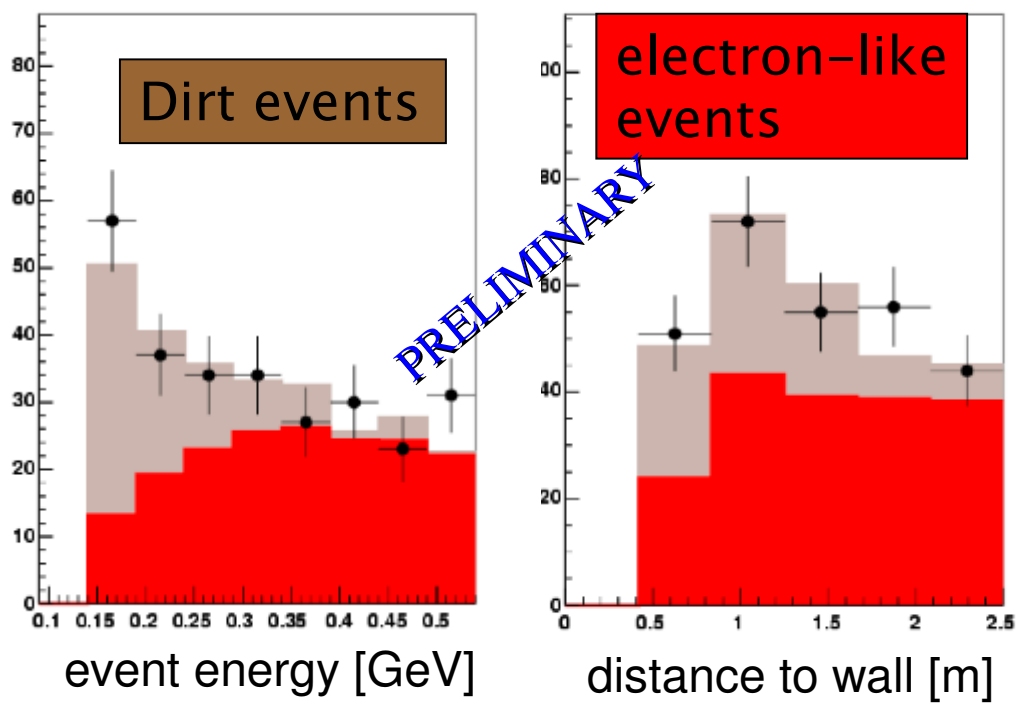
- Additional physics measurements:
  - Cosmic ray muons (J. de Jong in T8) and atmospheric ν_μ oscillations
  - Near detector cross-section measurements (D. Bhattacharya in F1)

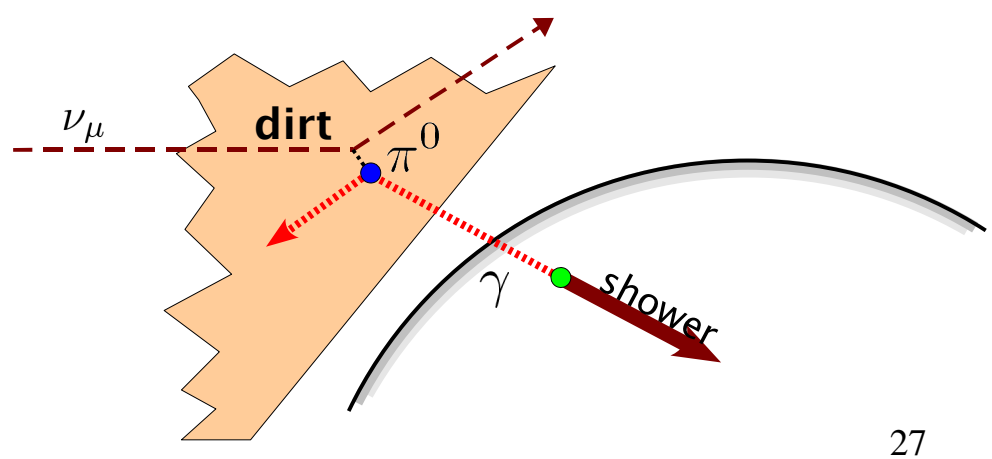
Backup slides

Numi@MiniBooNE: backgrounds

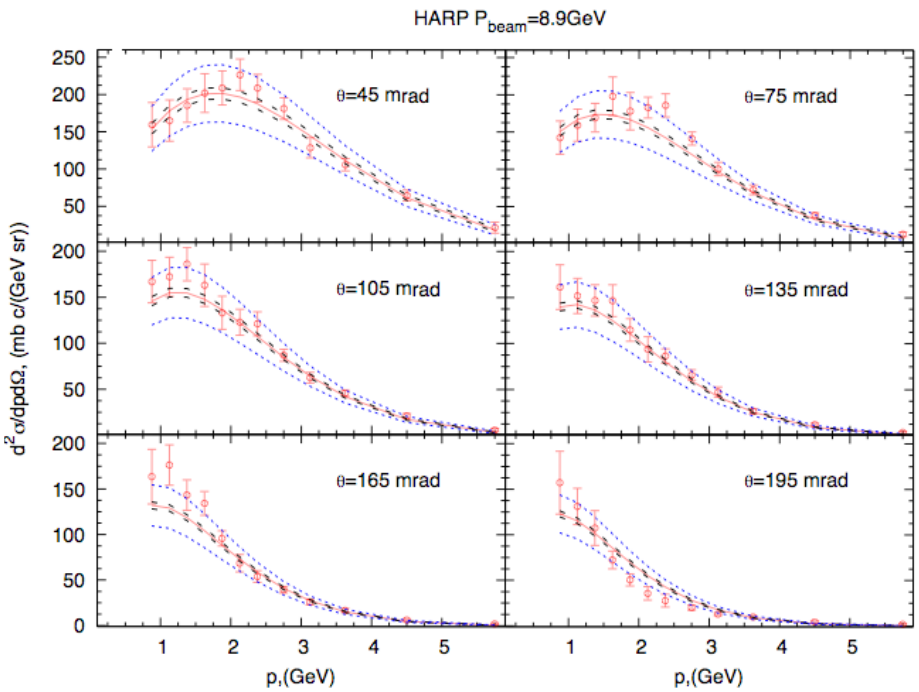
- Good data/Monte-Carlo agreement for π^0 events and dirt events
- Indepedent check of background estimates using NuMI beam

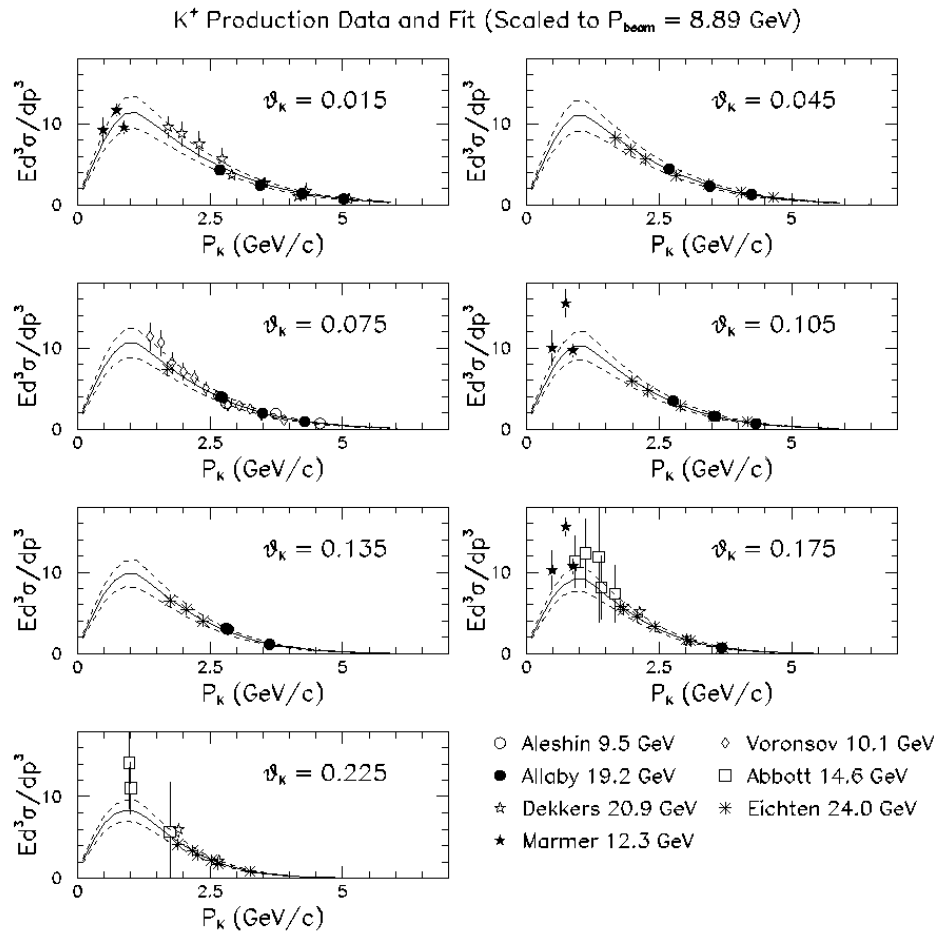






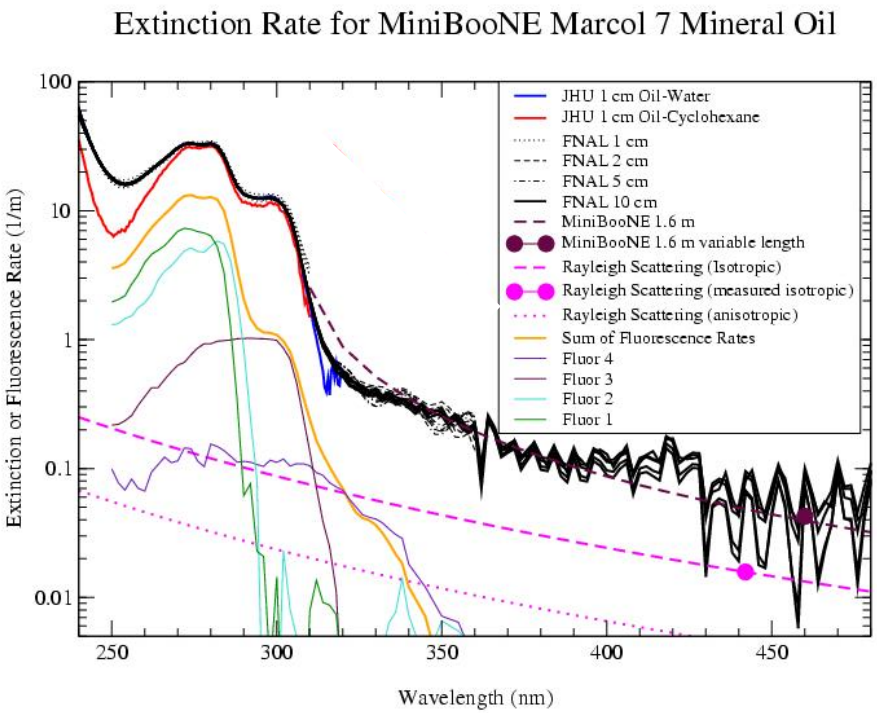
MiniBooNE flux

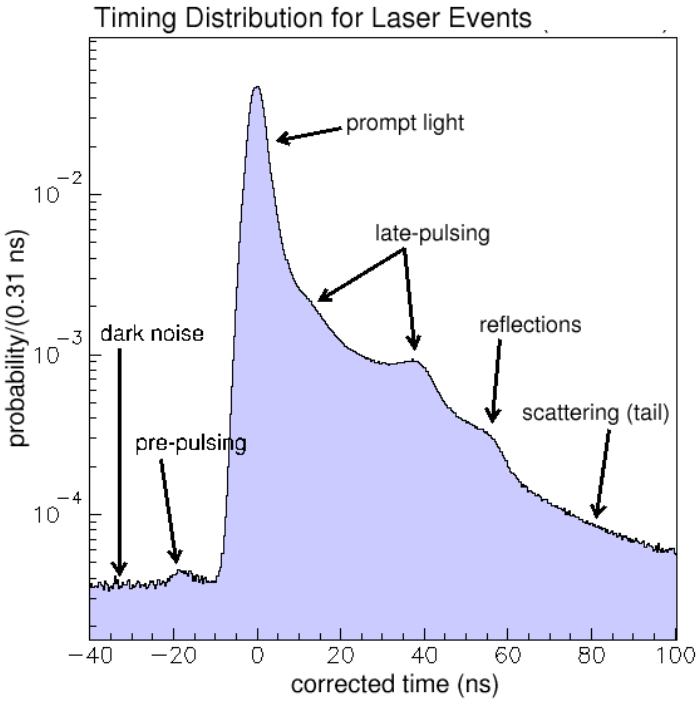




- Pion production were fit using HARP data
- Kaon production obtained from global fit

MiniBooNE optical model





- Complex optical model

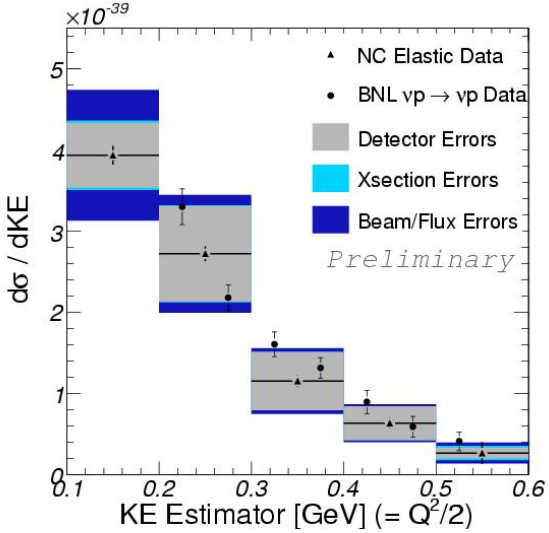
  Cerenkov, scintillation, fluorescence
  PMT Q/t response
  Scattering, reflection, prepulses

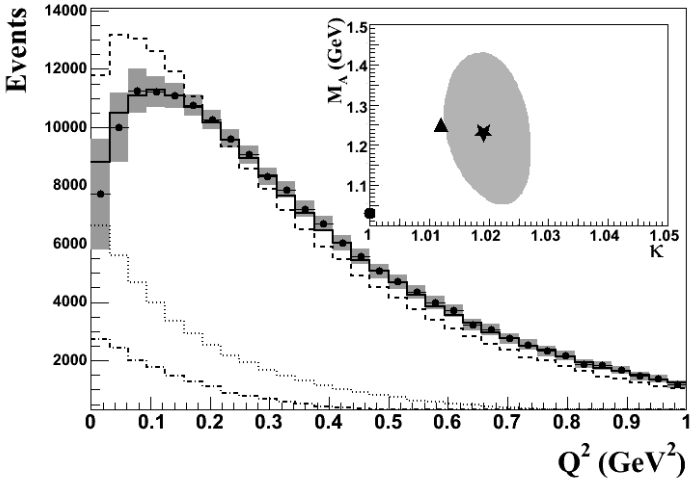
- About 40 non-trivial parameters

MiniBooNE systematic error

Source of uncertainty on ν_e background	TBL/BDT error in %	Constrained by MB data	Reduced by tying ν_e to ν_μ
Flux from π^+/μ^+ decay	6.2 / 4.3	√	√
Flux from K^+ decay	3.3 / 1.0	√	√
Flux from K^0 decay	1.5 / 0.4	√	√
Target/beam models	2.8 / 1.3	√	
ν-cross section	12.3 / 10.5	√	√
NC π^0 yield	1.8 / 1.5	√	
Dirt interactions	0.8 / 3.4	√	
Optical model	6.1 / 10.5	√	√
DAQ electronics model	7.5 / 10.8	√	

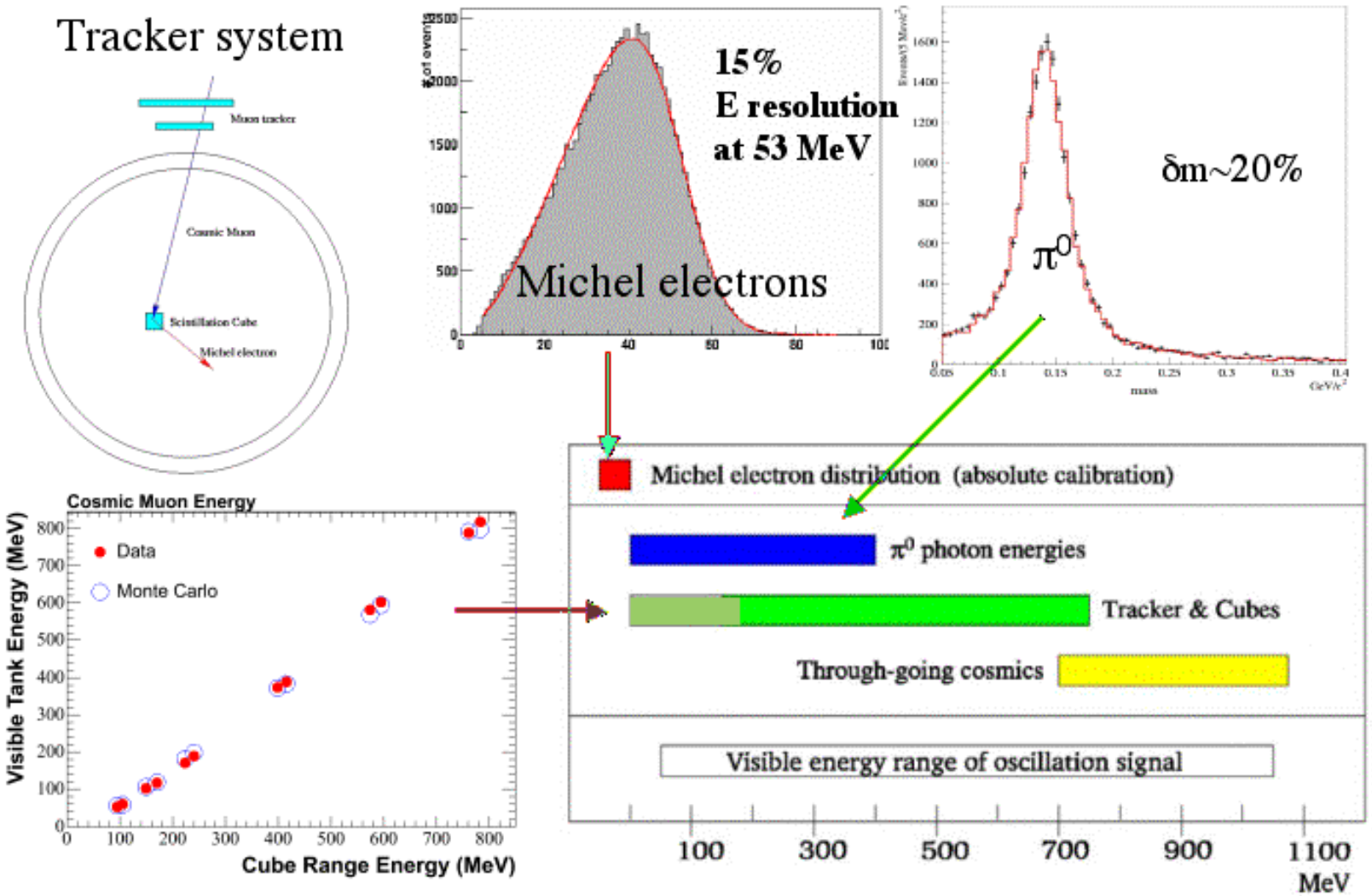
- All errors have some constraint from detector using beam or cosmic events and detector calibration system





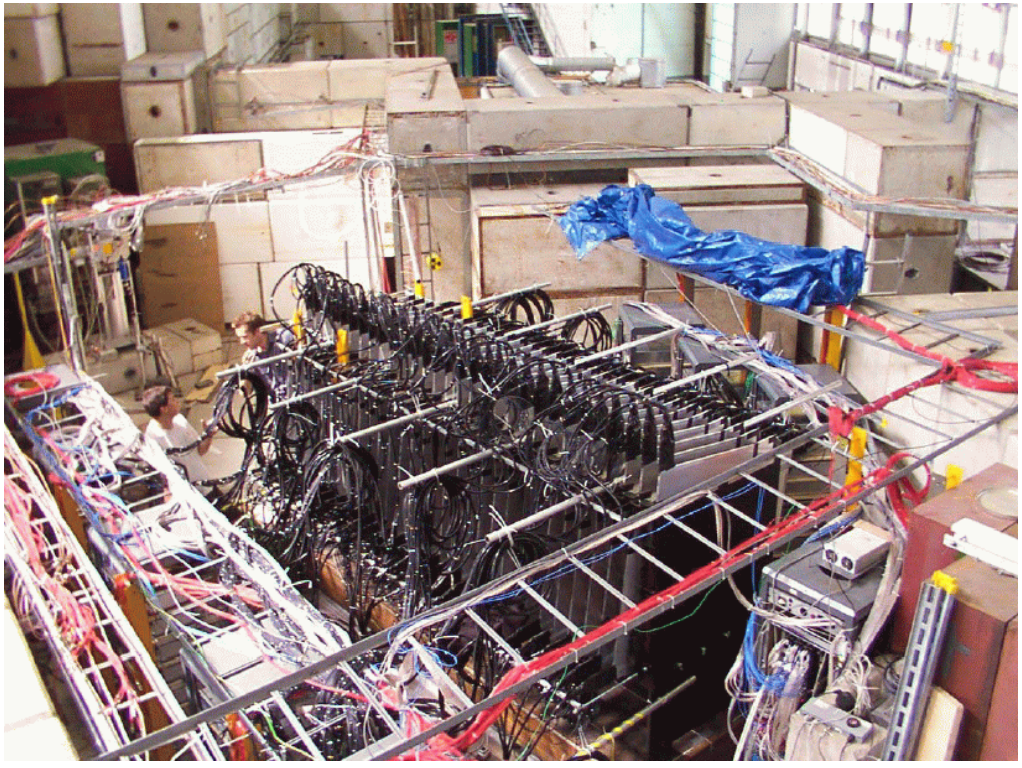
MiniBooNE calibration

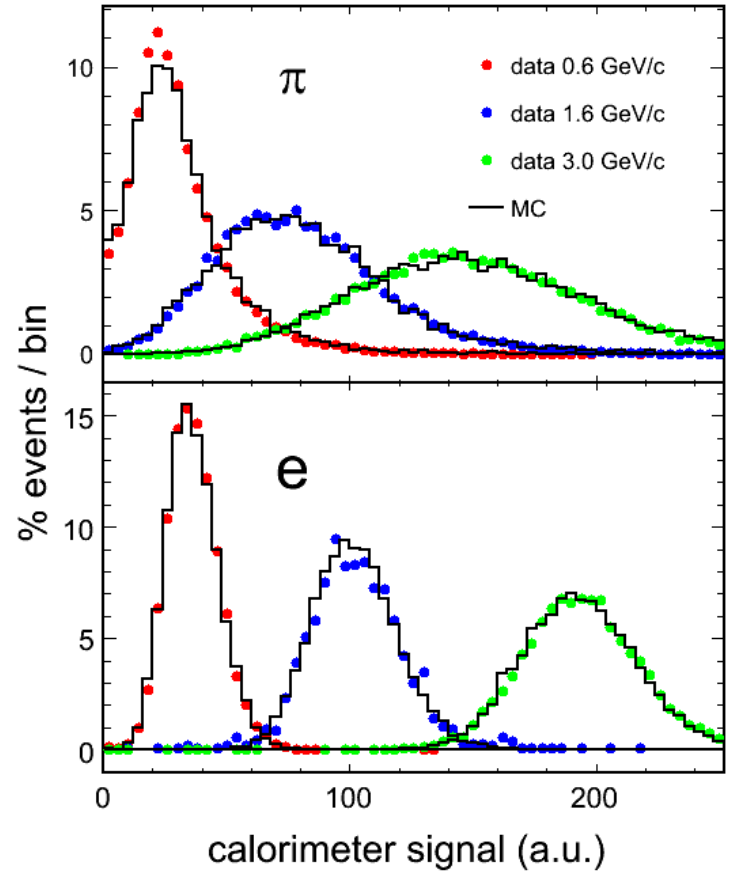
Calibration Sources

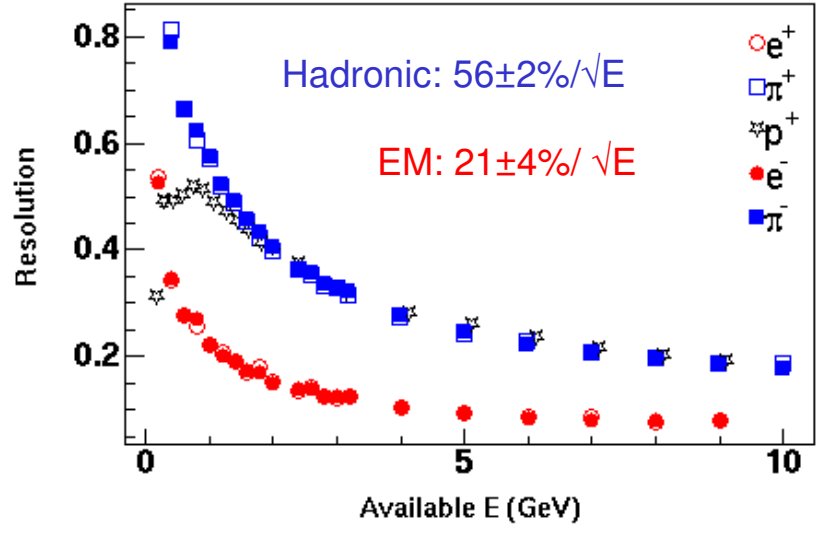


Caldet

- 60-plane 'micro-MINOS'
  - has taken data at T7 & T11 test beam lines at CERN during 2001, 2002, 2003
- Instrumented with both Near and Far Detector electronics
  - To provide cross-calibrations
  - Energy uncertainties: 3% relative, and 1.9% (ND) & 3.5% (FD) absolute

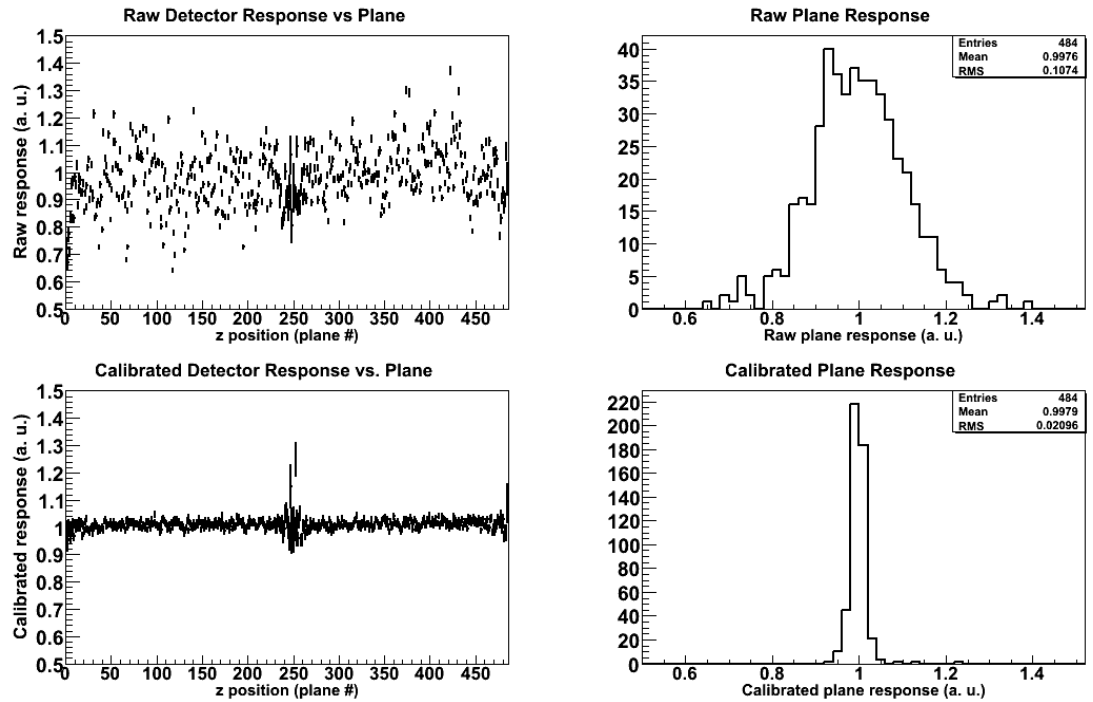


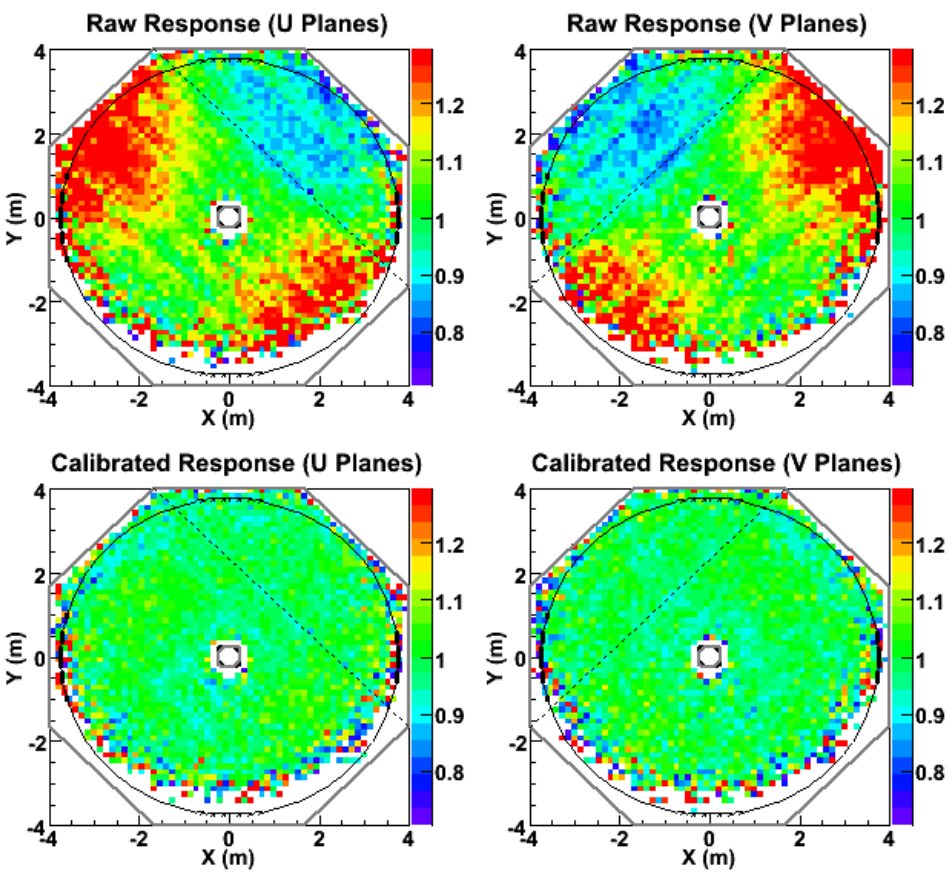




MINOS calibration

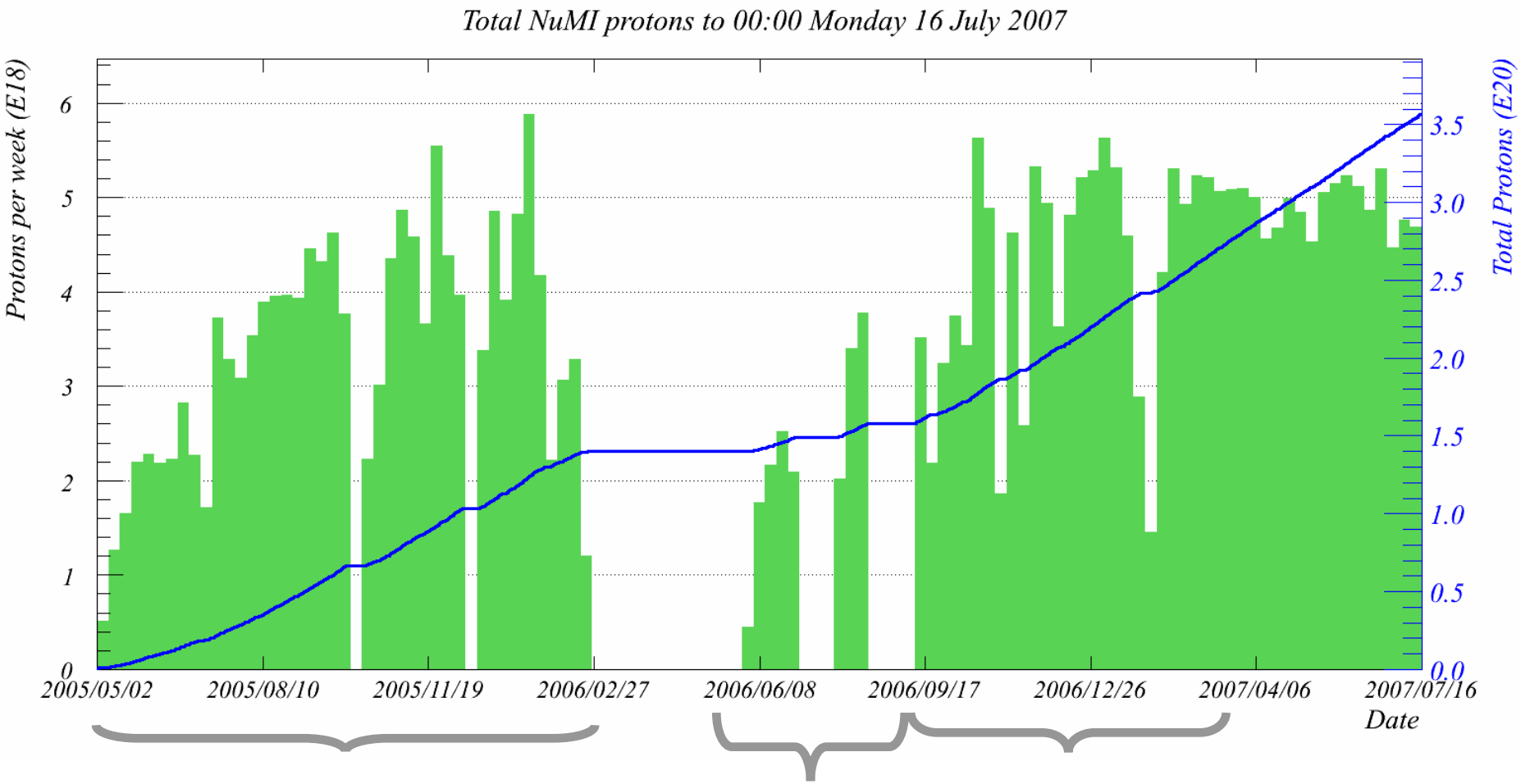
- Detectors are calibrated using LED ligh injection system and cosmic ray muons
- Absolute calibration with stopping muons





- Energy scale calibration:
- **3.1 % absolute error in ND**
- **2.3 % absolute error in FD**
- **3.8 % relative**

Numi@MINOS

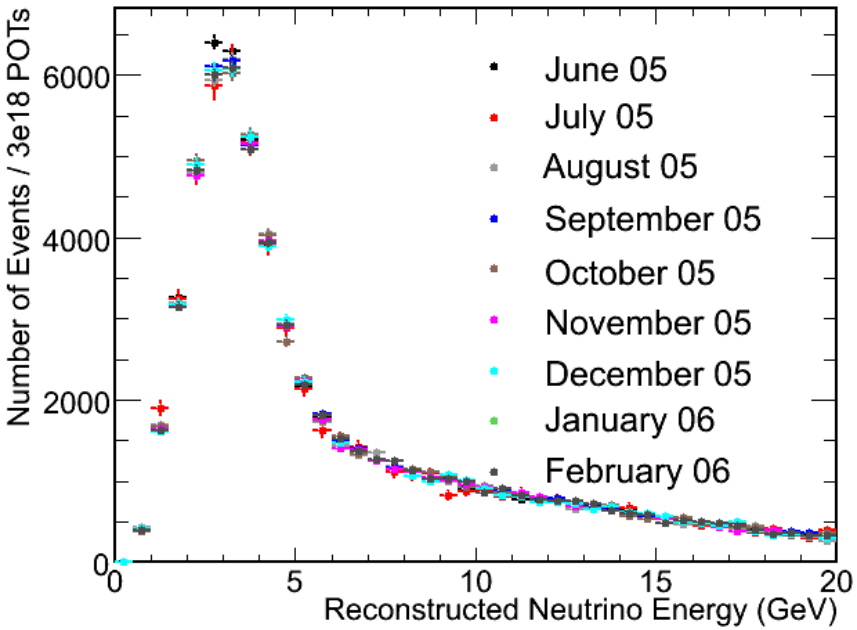


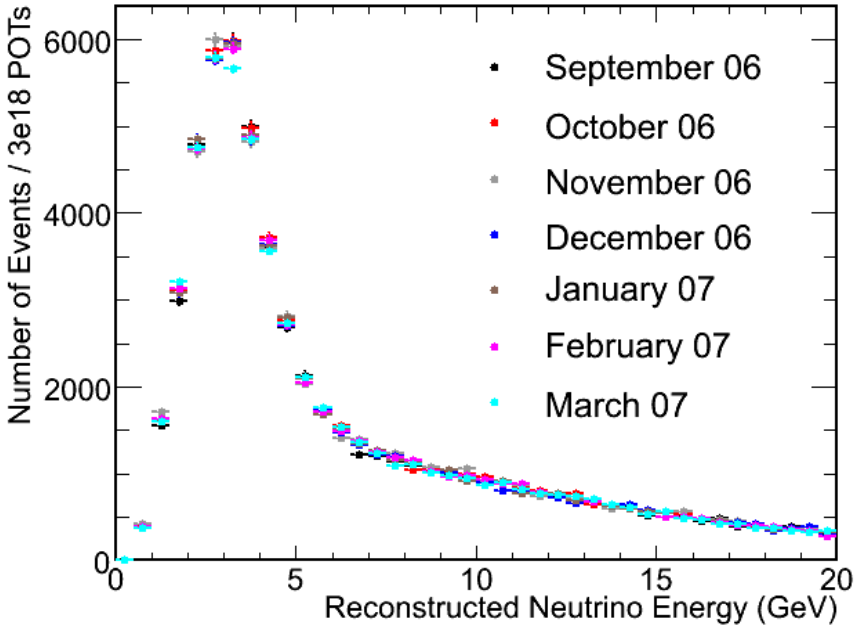
LE run 1:
1.27E20 protons

HE run 2:
1.5E19 protons

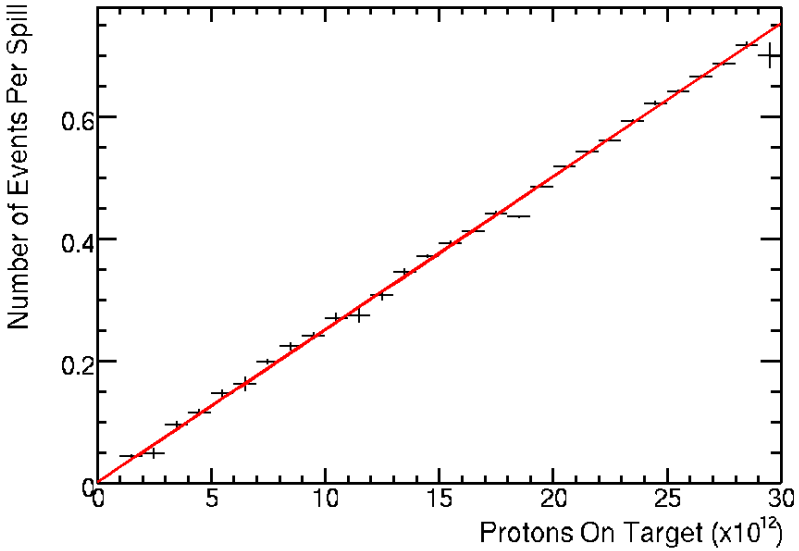
LE run 2a:
1.23E20 protons

Near detector stability



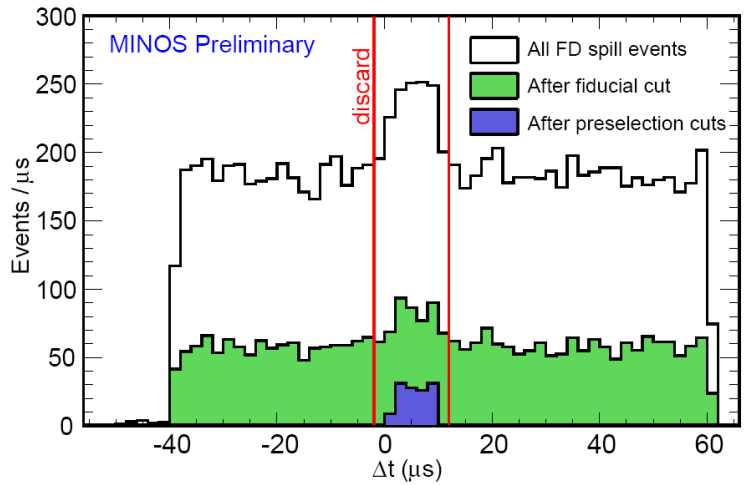


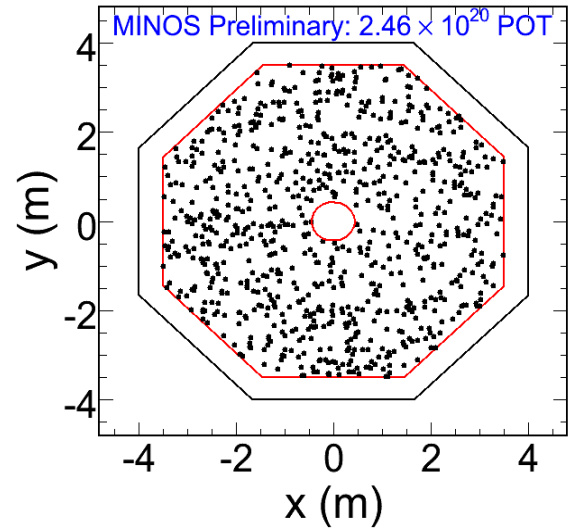
- Remove beam spills with "bad" beam properties: width and position at target, horn trips, etc
- Remove spills with bad detector state
- Selected spills are stabel with time
- Energy peak in Run 2 is 7%lower due to change in target position

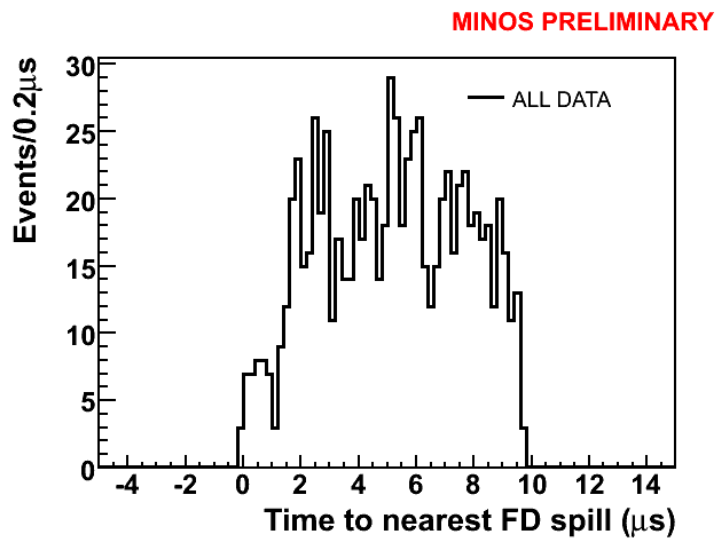


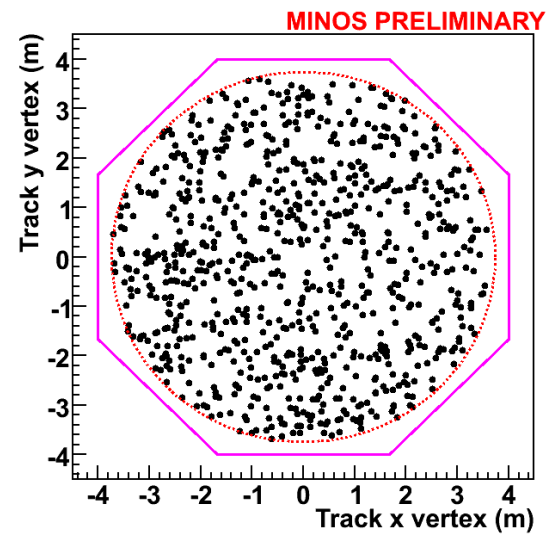
Far detector events

- Trigger far detector with GPS timestamp sent over Internet
- Select far detector events in time with beam spill using GPS clocks at near and far detectors
- Cosmic induced backgrounds are neglible in both NC(top) and CC (bottom) selected samples — check with "fake" spill triggers





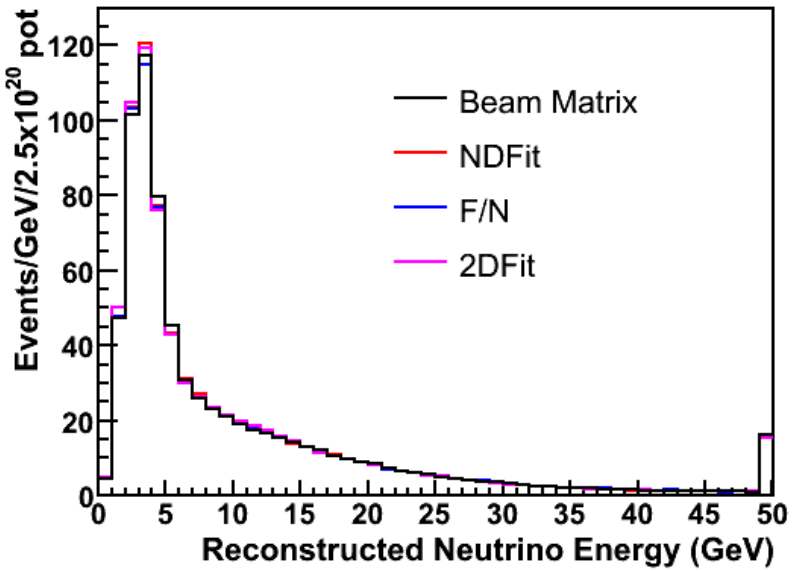


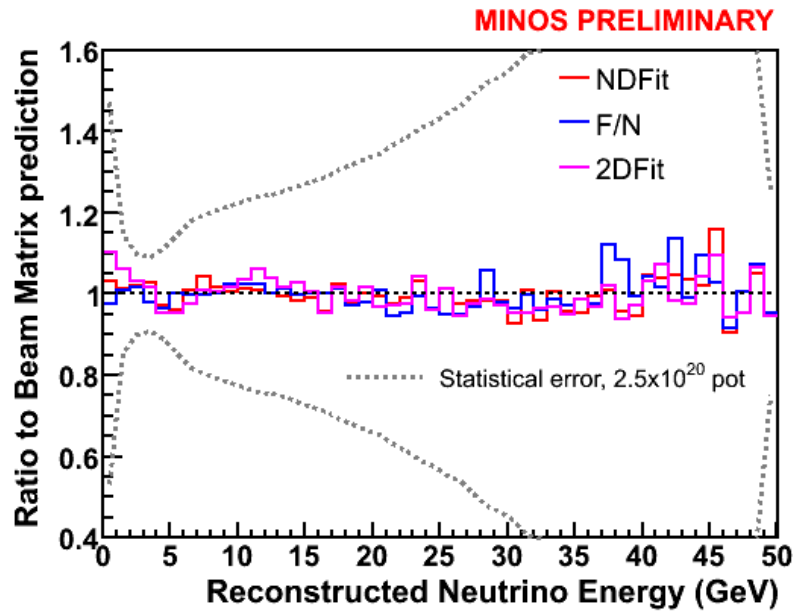


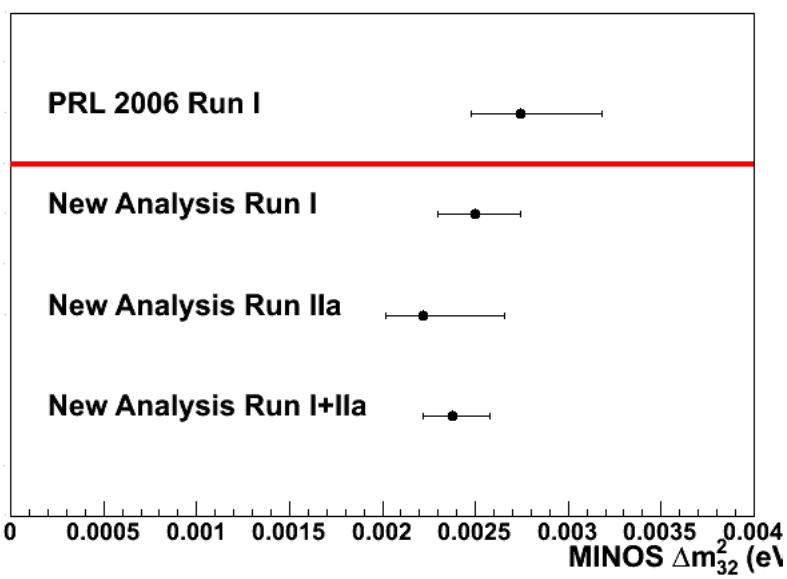
Far detector CC selection

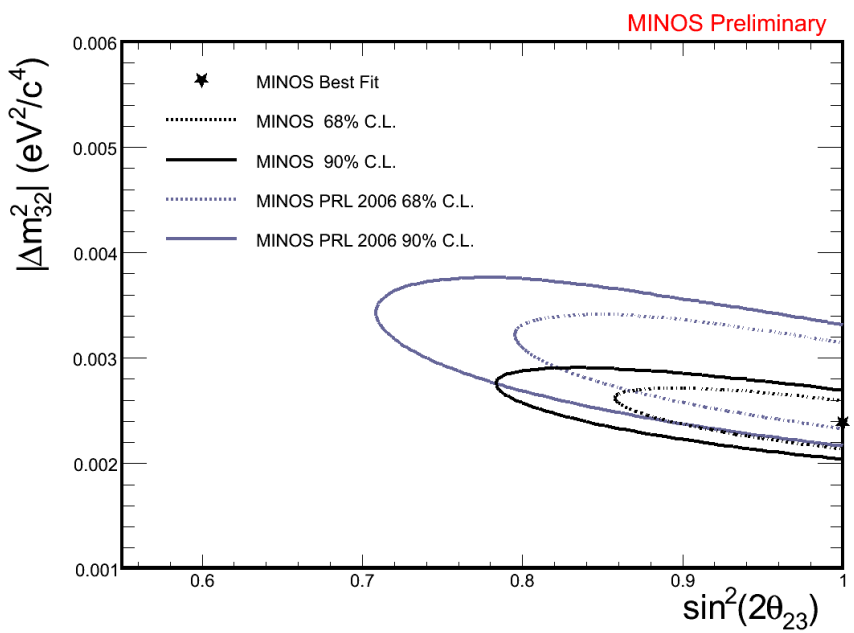
Cut	Number of Events
Track in fiducial volume	847
Data quality cuts	830
Timing cut	828
Beam quality cuts	812
Track quality cut	811
Track charge<=0	672
PID parameter>0.85	564
Reco Enu<200 GeV	**563** **Final Analysis Sample**

Far detector CC results



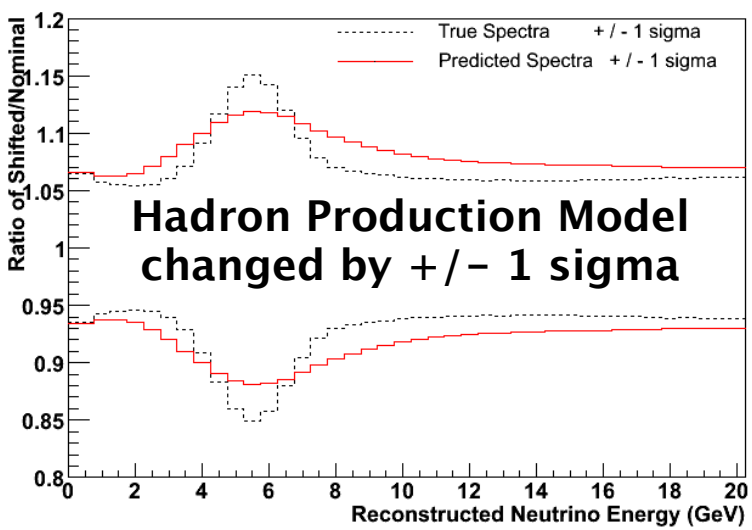


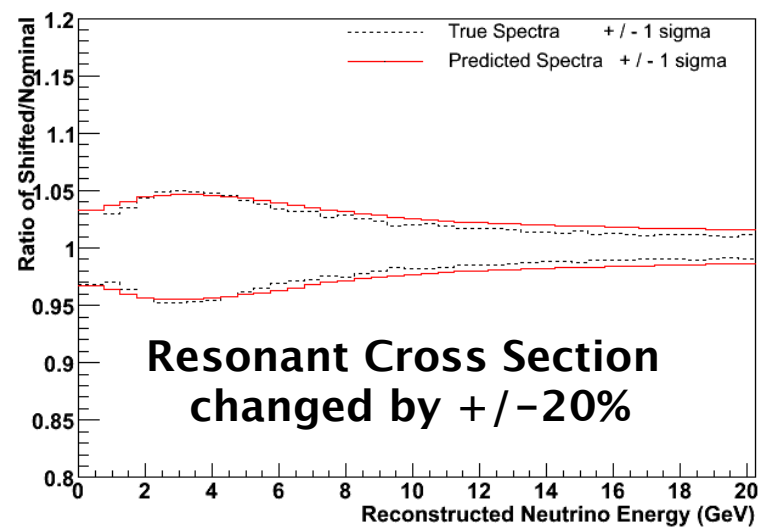




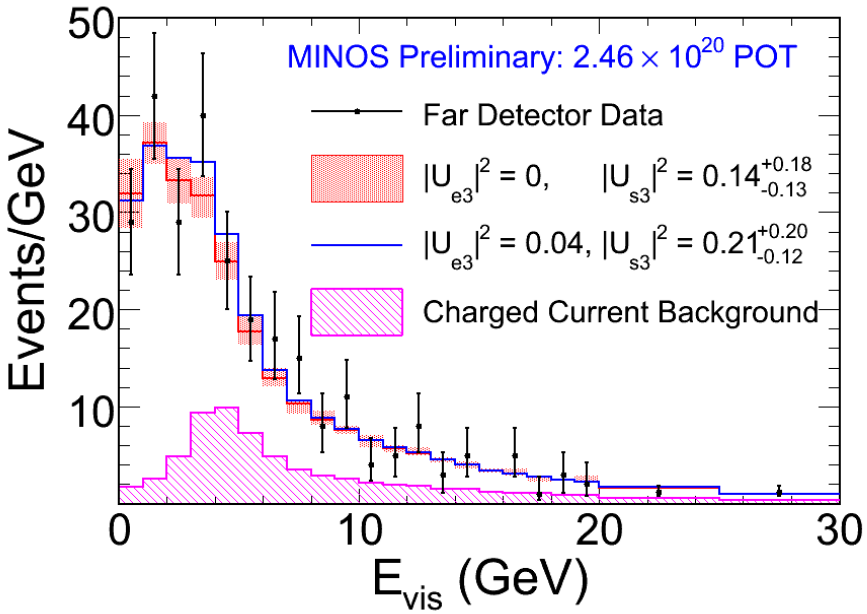
CC analysis systematic errors

Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2(2\theta)$
Near/Far normalization ± 4%	0.065	<0.005
Absolute hadronic energy scale ± 10%	0.075	<0.005
NC contamination ± 50%	0.010	0.008
All other systematic uncertainties	0.041	<0.005
Total systematic (summed in quadrature)	**0.11**	**0.008**
Statistical error (data)	**0.17**	**0.080**

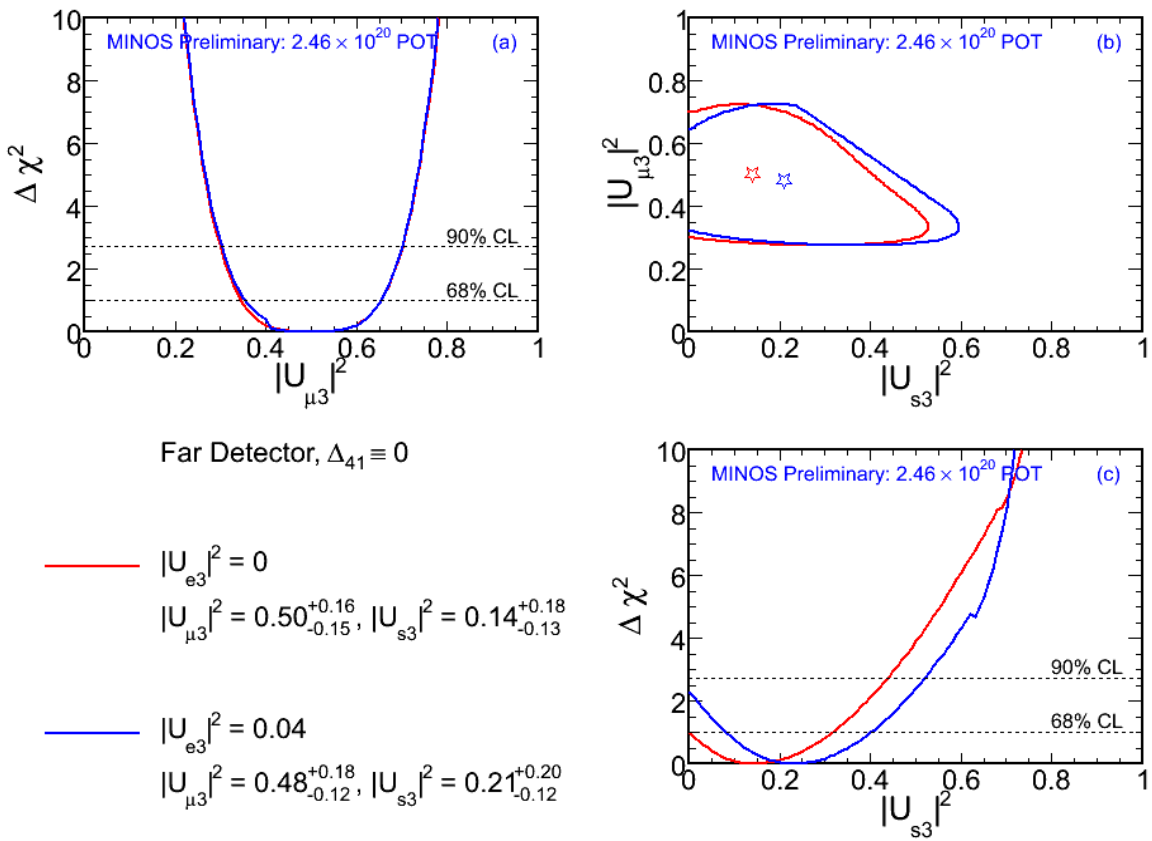




Far detector NC events



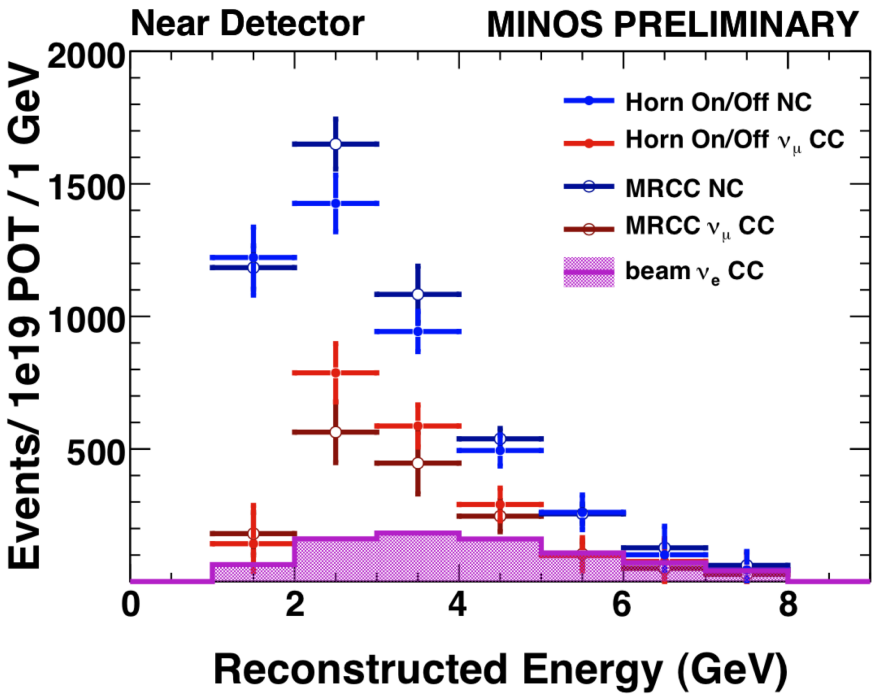
- Predicted NC events and data
- 4 flavors analysis



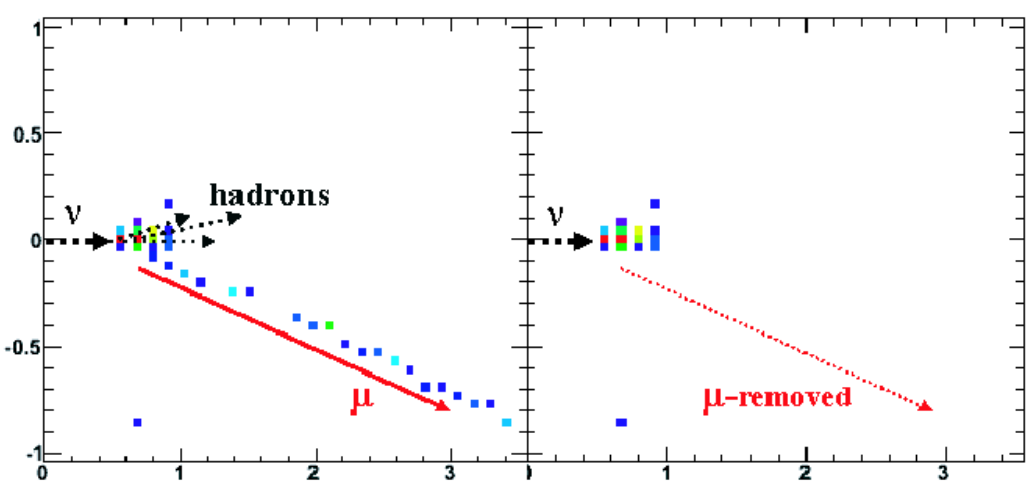
Far detector NC events

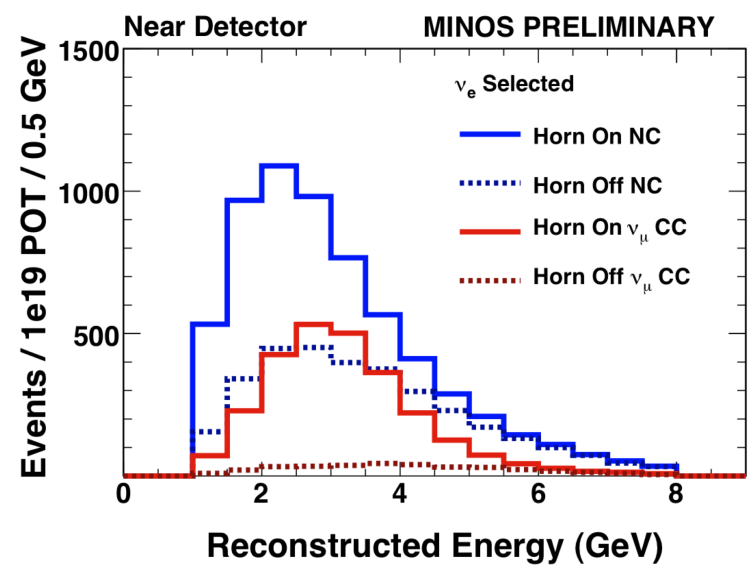
Uncertainty	Shift in $\|U_{s3}\|^2$	Shift in $\|U_{\mu 3}\|^2$
m_A	0.01	0.00
KNO	0.01	0.00
Beam uncertainties	0.00	0.01
Absolute Hadronic Calibration	0.01	0.02
Relative Hadronic Calibration	0.04	0.02
Muon Energy Scale	0.01	0.01
Normalization	0.06	0.03
CC Background in NC Spectrum	0.03	0.01
NC Background in CC Spectrum	0.01	0.02
Near Detector Selection	0.04	0.01
Poorly Reconstructed Events	0.00	0.00
Far Detector Selection	0.02	0.00
Total (sum in quadrature)	0.09	0.05
Statistical Sensitivity	0.18	0.18

MINOS ν_e appearance

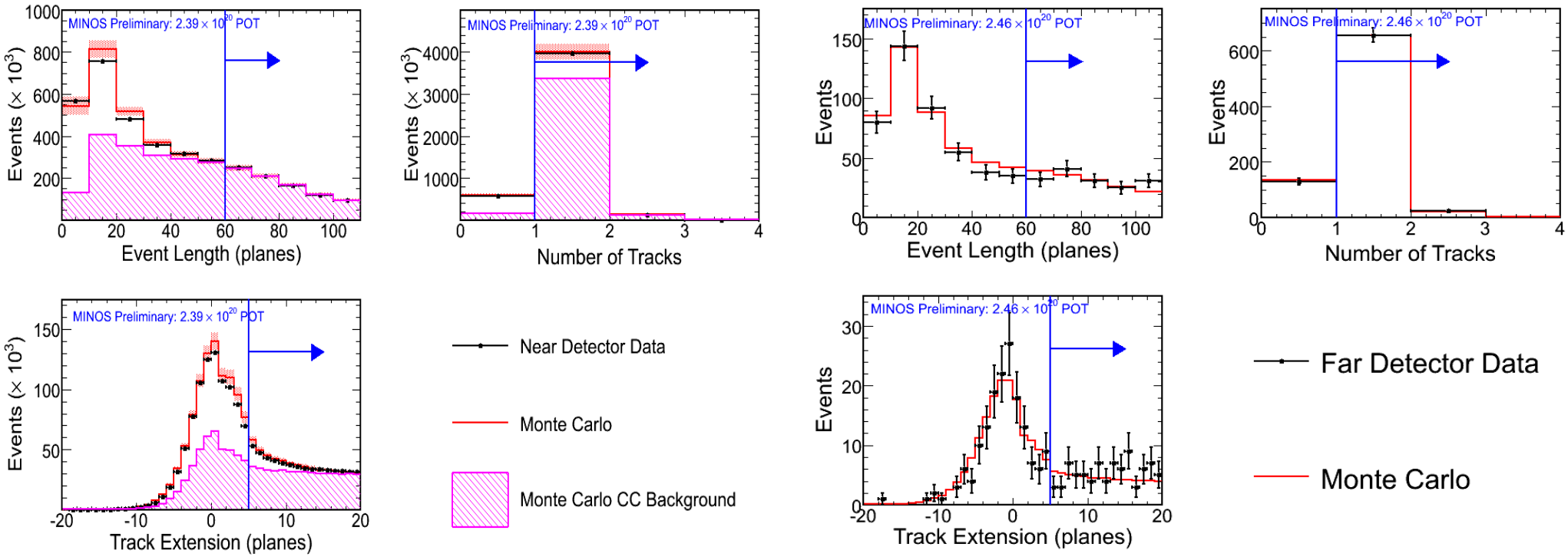


- Estimate two background components: NC and CCν_μ
- Two independent methods use near detector data events and agree with each other:
  - Muon removed events
  - Horn ON/Horn OFF beams





MINOS NC selection



- Select NC events with 3 simple cuts
- Same selection in boths detectors
- Reweight far detector CC background with best fit parameters from CC analysis